Adapting a human thermoregulation model for predicting the thermal response of older persons

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Abstract

A human thermoregulation model has been adapted for predicting the thermal response of Typical Older Persons. The model known as the Older Persons Model predicts the core body temperature and regulatory responses of the older people in environmental exposures of cold, warm and hot. The model was developed by modifying an existing dynamic human thermoregulation model using anthropometric and thermo-physical properties of older people. The Model defines the body as two interrelating systems of the body structure (passive system) and the control system of the central nervous system (active system).

The Older person's passive system of the model was developed by meticulously extracting relevant experimental data from selected published research works relating to anthropometric and thermo-physical properties of older people. The resultant body structure (passive system) is a multi-segmented representation of a Typical Older Person. The active system (central nervous system) was developed by the application of a novel optimization method based on the working principles of Genetic Algorithms. The use of Genetic Algorithm enables the complex characteristics of the central nervous system of the older persons to be well represented and evaluated based on available data. Active system control signal coefficients for sweating, shivering, vasodilation and vasoconstriction were explicitly derived based on experimental data sourced from literature.

The Older Persons Model has been validated using independent experimental data and its results show good agreement with measured data. Furthermore, the Older Persons Model has been applied to several test cases extracted from published literature and its results show good agreement with published findings on the thermal behaviour of older persons. An interview study conducted as part of this research revealed that, professionals (built environment specialists) found the Older Persons Model useful in assisting to further understand the thermal response of the older persons.

In conclusion, the adaptation of an existing human thermoregulation model has resulted in a new model, which allows improved prediction of heat and cold strain of the older person although there exist limitations.

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"And to all who are of equal mind towards the development of the world".

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Nomenclature

Dl	vasodilation command, W·K-1
Cs	vasoconstriction command
H	internal whole body heat load due to work, W
k	thermal conductivity, W·m-1·K-1
M	metabolic rate, W
r	radius, m
RH	relative humidity, %
S	rate of whole body heat storage, W
SH	shivering command, W
Sw	sweating command, g·min-1
T	temperature, K, °C
t	time, s, min, h
tanh	hyperbolic tangent function
w	perfusion rate, s-1
q_m	metabolism;
p_{bl}	density of blood;
w_{bl}	blood perfusion rate;
C_{bl}	heat capacitance of blood;
T_{bla}	arterial blood temperature;
Δ	difference
ΔT	temperature error signal
Δt	time step
η	efficiency
ρ	density
ω	geometry factor
σ	Stefan-Bolzmann
Ψ	view factor between the
T_{skm}	Mean skin temperature
T_{hy}	Hypothalamus temperature
T_{re}	Rectal Temperature
R^2	Coefficient of determination

T_{ty}	Tympanic temperature
T_{sw}	Thresholds of cessation of sweating
Yrs.	Years
WA	Weighted Average
PMV	Predicted mean vote
PPD	Predicted percentage dissatisfied
ACE	American Council on Exercise
RMSE	Root mean square error
Mins	Minutes

Chapter 1

General Introduction, Aims and Objectives

1.1 Introduction

This chapter introduces the reader to the background, the context and the need for the research. It also outlines the structure of the thesis.

1.2 Background

The population of the world is ageing rapidly in both developing and developed countries. In less than a century, particularly in the developed world, there has been an average 30 year gain of life expectancy (ILC, 2009). This phenomenon could be associated with declining fertility and improved health care delivery leading to low levels of mortality which in one sense represents a human success story of increased longevity (UN, 2001). However; the steady, sustained growth of older populations also poses many challenges to policy makers, building designers and built environment specialists. Indeed in household where older persons are present the pattern of use of heating and ventilation system are affected (Guerra-Santina and Itarda, 2010). This may be due to the susceptibility of older people to declining health and possible loss of some thermoregulatory functions (WHO, 2004).

1.3 The Ageing World

Harman (1981) defines ageing as "*the progressive accumulation of changes with time that are associated with or responsible for the ever-increasing susceptibility to disease and death which accompanies advancing age*".

Florez-Duquet and McDonald (1998) refers to it as *"the inability of the organism to maintain homeostatic regulation when given a challenge"*.

In general, it has been reported that the average age of the world's population is increasing at an unprecedented rate (Kinsella and He, 2009). It is estimated that worldwide, between 1970 and 2025 the proportion of people over 60 years of age are growing faster than any other age group (WHO, 2002). Bloom et al. (2011) suggests that the number of people over the age of 60 years is expected to reach 1 billion by 2020. This number is expected to reach almost 2 billion by 2050 representing 22 percent of the world's population. Certainly one of the most significant aspects of the ageing of populations around the world is the ageing of the older population itself. In many nations around the world persons aged over 80 years are growing faster than the younger segment after 60 years (Kinsella and He, 2009). Projected figures point to a rise of 1% to 4% of total global population by year 2050 leading to a high likelihood of persons aged 65years and over expected to be more than children under 5 years for the first time in history (Kinsella and He, 2009) see Figure 1.1.

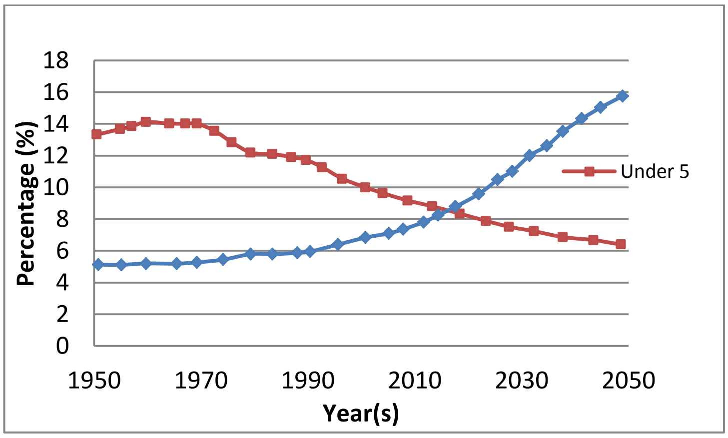

Figure 1.1 Young children and older people as a percentage of global population (Kinsella and He, 2009)

1.4 Ageing and the Human body

Research has revealed that as we age many changes occur in the human body including reductions in (cardiovascular functions, basal metabolism, muscle mass and regulatory responses) affects its ability to function properly (Novieto and Zhang, 2010). In the skin, collagen fibres decrease in numbers and stiffen with the elastic fibres losing their elasticity and production of sweat diminishes which probably contributes to the increased incidence of heat stroke in the elderly (Tortora and Derrickson, 2007a).

Stevens and Choo (1998) in their work, 'looking at temperature sensitivity of the body surface over the life span' concluded that with age, temperature sensitivity declines. In the endocrine system, the thyroid gland often decreases its output of thyroid hormones with age causing a decrease in metabolic rate and increased body fat (Tortora and Derrickson, 2007a). Kenney and Munce (2003) indicated that, comparing older adults with young adults, in the event of heat stress, "*older individuals typically respond with reduced individual sweat gland outputs, decreased skin blood flows and reduced cardiac outputs".* In extreme cases, such as during extreme weather events, this may result in excessive thermal strain on the body to maintain constant internal temperature (Novieto and Zhang, 2010).

In the cardiovascular system, there are increases in the stiffness of the aorta and decline in maximum heart rate as a result of ageing with an associated reduction in the cardiac muscle fibre size and progressive loss of cardiac muscular strength (Tortora and Derrickson, 2007a). Many studies have also found reduced cardiac output in the older person (Taylor et al., 1992, Payton and Poland, 1983) coupled with an increased systolic blood pressure. Redfern and Ross (1999) found significant reduction in the efficiency of vasoconstrictor response in the elderly in response to cold as a result of ageing. In many instances older persons do not constrict as expected on cooling which may be as a result of autonomic dysfunction related to age. As a result, health, wellbeing and even life may be at risk. Research in thermal physiology and medical studies found that changes in many parts of the human body may contribute to the reduction in thermoregulatory functions placing older persons are at increased risk of both hypothermia and hyperthermia when exposed to extreme temperatures (Van Someren, 2007).

By the time a person reaches 90 years of age, there is a reported decrease of 10 to 20% in the weight of the brain (Payton and Poland, 1983, Esiri, 2007). This may likely lead to decreased capacity in sending nerve impulses to and from the brain which may result in diminished processing of information, decreased conduction velocities and reduced voluntary motor movements (Tortora and Derrickson, 2007a). Older person's ability to detect (sense) temperature at the extremities of the body including the arms, legs appears to be increasingly reduced as a result of ageing (Anderson et al., 1996). Ageing also affects the neurosensory system of the body and these changes tend to delay or diminish the older person's awareness of temperature changes and may likely impair behavioural and thermoregulatory responses to dangerously high or low environmental temperatures (Ebersole et al., 2004). Without a doubt many research publications have pointed out that, the changing of the earth's climate leading to more extreme weather conditions may likely impact the health and wellbeing of the older population (Harvison et al., 2011, Beniston, 2002).

1.5 Climate Change

Houghton et al. (2001) defines climate change as

"The state of the climate that can be identified by the changes in the mean and or the variability of it properties and that persists for an extended period, typically decades or longer".

Over the years variations have been observed in the state of the earth's climate but recent changes in climatic conditions are occurring much rapidly (Harvison et al., 2011). The current variations in climatic conditions is expected to increase average summer temperature and the frequency and intensity of hot days (WHO, 2004). Houghton et al. (2001) points out that there is a direct link between the accelerated warming of the global temperature and human activity. Over the last 140 years, estimated figures point to an increase of 0.6 ± 0.2°C in global average surface temperature. Usually new record extreme events occur every year somewhere around the globe but recent years have witnessed a rise in the numbers of such events (WHO, 2004). As it is, even if the statistical distribution of such events remains the same, a shift in the mean will lead to new record high temperatures (Figure 1.2) which may have adverse effect on the older people.

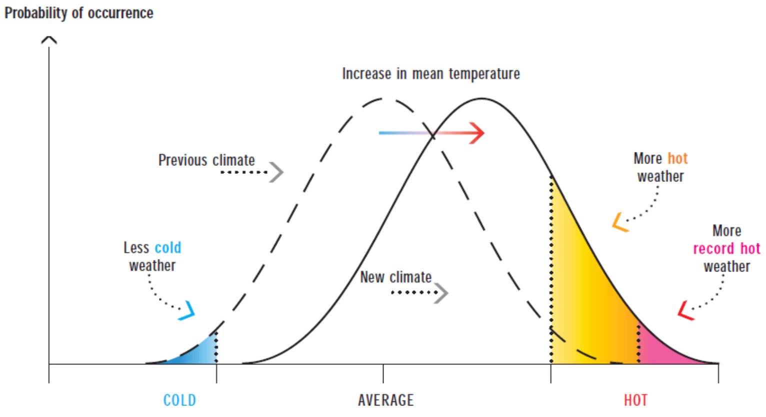

Figure 1.2 Mean temperature variability (Houghton et al., 2001)

1.6 Ageing and Vulnerability to Climate Change

The sensitivity of the older population is an issue which calls for more attention since to a greater extent, they are likely to suffer more than any age group as a result of the impacts of change in earths climatic conditions (Harvison et al., 2011). Older people are noted to be amongst the most at risk due to many factors including decreased mobility as a result of age, changes in physiology and reduced adaptive capacity (Filiberto et al., 2009).

Robinson (2001) defines heat wave as "*an extended period of unusually high atmosphere-related heat stress which causes temporary modification in lifestyles and which may have adverse consequences for the affected population*".

In August 2003, more than 2000 deaths were attributed to the heat wave in England and Wales, (Kovats et al., 2006). During that period, excess mortality was 33% in those aged 75 years and over, compared to 13.5% in the under 75 years age group with the greatest occurring in nursing homes where deaths increased by 42% (Kovats et al., 2006)**.** Statistics in France show a strong correlation between excess death and age during the heat wave. The excess mortality was estimated at 20% for those aged 45-74 years, and 70% for the 75-94 year age group (Pirard et al., 2005)**.** Despite the extreme events like the heat waves, excess mortality amongst the elderly mainly occurs in the winter months, when lack of warmth and hypothermia pose a major threat (Healy, 2003). Figures from the Office of Nations Statistics UK (ONS, 2012) show that overall, there was an estimated 24,000 excess winter deaths in England and Wales for 2011/2012. Of this figure majority of the deaths (over 80%) were amongst those aged 75 years and above with only 4,500 for those below 75 years. For the older adults the changing climate makes them more venerable to the environmental risks associated with it which may have negative impact on their lives (Filiberto et al., 2009).

1.7 Ageing and the Built Environment

Buildings in general exist to act as envelopes to protect occupants from the adverse effects of the weather.

According to PMSEIC (2003) *"The built environment has a powerful impact on mobility, independence, autonomy and quality of life in old age and can also facilitate or impede the quest for a healthy lifestyle"*

Buildings in particular serve as an interface between the outdoor environment which is affected by change in climatic conditions and the indoor environment which needs to be maintained at a comfortable range for the occupants (Pieter de Wilde and Coley, 2012). With recognition being given to issues of the ageing populations around the world and the changing of the world's climate, one key question which is also gaining prominence is,

"can the built environment be designed or adapted to assist older persons cope and maintain a healthy lifestyle?" (Harvison et al., 2011).

In recent times, there has been considerable research aimed at exploring issues raised by this question. Porritt (2010) found that in normal family settings, the homes are unoccupied during the day but that is not the case where older persons are part of the household. In most cases, the older residents occupy the living rooms during the hottest part of the day. As a result they can be subjected to higher temperatures beyond what they can comfortably tolerate. Porritt (2010) therefore concluded that, there is the need for those responsible for adapting buildings to climate change to have both detailed information about the building fabric and also occupancy profiles when choosing appropriate interventions. Hwang (2010) reported that older people tend to spend more time at home compared with other age groups. In some cases, 100% of their time is spent indoors (Mercer, 2003). This may not be surprising, especially taking cognisance of their activity levels and capability in terms of their ability to move around. Older people are also physiologically and psychologically diverse, and thus have different requirements toward indoor microclimate from other age groups (Hwang and Chen, 2010) and this may invariably affect their thermal balance.

In exploring the above question, it is important to firstly identify what specific thermal needs or sensitivities that older persons may have and to which the built environment will respond to (Harvison et al., 2011). To achieve this aim there is a need for a tool which allows for the critical analysis of the human systems reactions to the change in environmental conditions and which can also be used to explore the extremes of human reaction in severe environmental stress without putting life at risk. One feasible tool is the human thermoregulation models and indeed they appear to be appropriate due to their detailed representation of the human body.

1.8 Human thermoregulation modelling

Modelling of the human body thermal response has been in existence for some time now (Pennes, 1948, Stolwijk, 1971). Over the years, many researchers have developed mathematical thermal models using different approaches, such as analytical, statistical, empirical and physiological models, to predict and better understand human thermal responses (Jang, 2009). These models simulate the phenomena of human heat transfer inside the body and at its surface taking into account the anatomical, thermal and physiological properties of the human body (Fiala, 1998). Environmental heat losses from body parts are modelled considering the heterogeneous distribution of temperature over the body surface. These models are thus capable of predicting ‘local’ characteristics such as skin temperatures of individual body parts (Ohba et al., 2010) and the total thermal comfort state of the body (Fiala, 1998). One of the earliest attempts at model development was made by Pennes (1948) who developed a steady-state model to analyse heat transfer in a resting human forearm. Thereafter, a more advanced model was developed by Stolwijk (1971) and Wissler (1985). Subsequent advances in computing technology and increased experimental data on human physiology helped researchers in developing more sophisticated human thermoregulation models (Jang, 2009).

Human thermoregulation models are valuable tools used in predicting and understanding the thermal response of the human body under different environmental conditions and activity levels (Salloum et al., 2007). Most of them have been developed to predict the thermal comfort of a person in a given environmental condition. Thermal comfort, defined as “*the state of mind which expresses satisfactions with the external environment”* (ANSI/ASHRAE, 2010) may be estimated based on the predictions of the models. These models have unique abilities of being used both to improve comfort of the thermal environment and also to assess the risk of exposure to various environmental conditions (Alfano, 2008).

In the built environment where we spend most of our lives, there are different types of micro climate that we come into contact with as part of our daily routines and activities. These micro-climates could be mild or sometimes severe and our body's thermoregulation system has to constantly deal with this variation. Interestingly, health and wellbeing of older persons are noted to be affected as a result of how thermally comfortable they are (Zhang and Novieto, 2010).

1.9 Ageing and Human thermoregulation Modelling

Currently, most human thermoregulation models in existence have been developed to represent an average person. This may be as a result of the fact that, data which was used in their development mostly came from young person exposed to different environmental conditions. In reality, validities of these models are limited in most cases to predictions of young persons. Indeed typical characteristics of ageing in human body organs and systems have not been incorporated in their design. Despite the rise in the development and sophistication of human thermoregulation models over the years, specific models for the simulation of thermal response and behaviour of older people have not been greatly considered. This may be due to the lack of adequate experimental data or the Ageing society issues were not as prominent as they are today. Crews (2007) reports that until recently, there was

> *"Little need to design environments for the unique and specific needs of elderly members of our populations due to their low representation"*.

However, in recent decades, older people's numbers have increased considerably with the likelihood of one fourth of the population in many nations predicted to be 60 years by 2020 (ILC, 2009). Research has also revealed that, there exist a body of scientific research data available in the areas of human biology, physiology, psychology and sociology relating to ageing. Also, awareness about the need to consider age-related functional and mental losses among the older population when designing artificial environments has also increased (Crews, 2007). Indeed when a model's prediction was compared to measured results, it was discovered that there were discrepancies, as a result, Van Someren (2007) concluded that for effective age related studies, these models need to be adapted.

1.10 Problem Definition

Taking cognizance of the major issues highlighted which includes:

- The ageing of populations around the world with the proportion of individuals aged 80 or over projected to rise from 1% to 4% of the global population by 2050 (Kinsella and He, 2009),
- The changing of the earth's climate leading to raise in temperatures and weather variability (Houghton et al., 2001) which may exacerbate the threats to human health (especially that of the older people) posed by thermal stress and
- The current thermoregulation models which have been designed to predict comfort of average persons without much consideration given to the anatomical and physiological sensitivities of the elderly,

The need to design a model, which can be used to determine the thermal behaviours of the older persons, cannot be overstated. Figure 1.3 shows the inter-relationship between the major issues highlighted which defines the aim of the study.

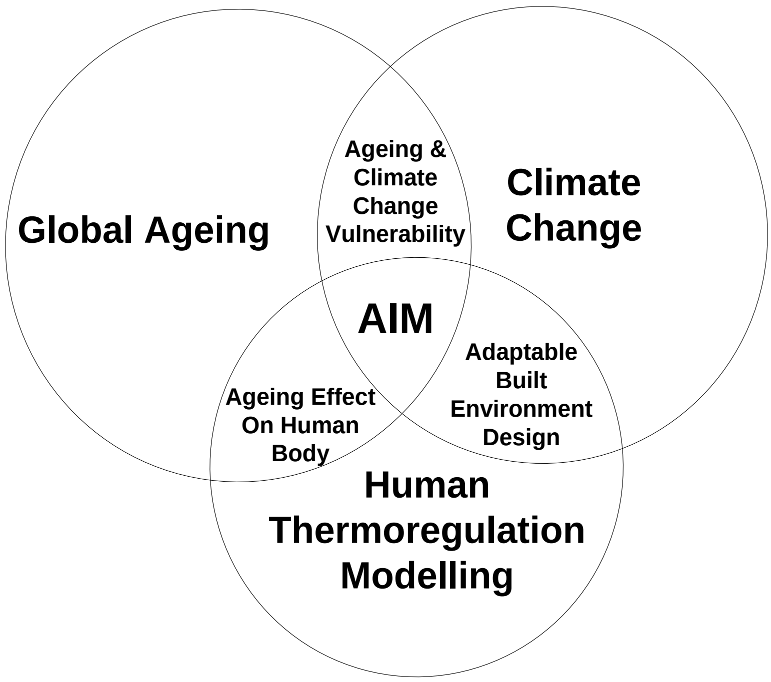

Figure 1.3 Inter-relationships between the major issues of concern

1.11 Aim and Objectives

Aim

The overriding aim of this research is to:

Develop a customized human thermoregulation model which can be used for predicting the thermal response of older persons.

In order to achieve this aim, the following individual objectives were determined

The individual objectives to meet this aim are:

- To highlight issues of ageing of populations around the world and describe how ageing affects the human body and its regulatory systems.
- To conduct detailed literature review to collate and extract relevant data from published experimental test cases of older persons to be used for model development.
- To develop a model of older persons passive system and verify it.
- To develop a model of older persons active system using a novel optimisation approach
- To verify and validate the complete model using experimental data sets in cold, warm and hot environments.
- To test model utilization by applying it in real life test cases extracted from published literature.
- To conduct interview study aimed at eliciting feedback from practitioners on the potential applications of the model.

1.12 The value of solving the problem

The development of a thermoregulation model for older population is an attempt to produce a tool which can be used to illuminate priorities especially, designers and built environment specialists should consider when designing/managing occupancies for the older people. This can be done by pre-testing various design scenarios and analysing their effects on the thermal state of the older person and possible energy use considering the change in climatic conditions. Major stakeholders who may benefit from the model include:

- **Policy makers:** As reported by Kovats (2006), during the last major heat wave (August 2003) excess mortality occurring in nursing homes increased by 42%. It is hypothesised that, the new model will provide nursing/retirement home managers with a tool which can be used to support orientation programmes for staff and some residents since as reported by Brown (2010), residents are exposed to excessively high temperatures through the action of disciplinary power which seeks to control and reform residents by holding them in place. Brown (2010) also found that;

  "*hierarchical power structures prevent many of the home's staff and residents from interacting with the heating and cooling technologies available, therefore in the event of hot weather they are unable to take appropriate action".*

- **Designers:** The model can be used to test case scenarios which will illuminate the priorities they should consider in the event that the accommodation being designed or retrofitted will have elderly occupancy. Porritt (2010) highlights the need to critically analyse occupancy profiles in conjunction with details of building façade, in that unlike typical family scenarios where the houses are unoccupied during the daytime, in situations where there are elderly residents, the profile is affected. *"Most at time the older persons occupy the living rooms during the hottest parts of the day and are subjected to temperatures which may be beyond their comfort thresholds"* Porritt (2010).

- **Researchers:** This will serve as a tool to further enhance the understanding of the ageing effect on the human body and it thermal balance. It can also be used to further test scenarios which cannot be carried out experimentally (e.g. very high or very low temperature exposures) due to the sensitivities of the older people and health considerations.

1.13 Research Methodology

In order to develop a human thermoregulation model for predicting the thermal response of older persons, a multi-method approach was used. This was selected as the study largely involves the adaptation of an established thermoregulation model using experimental data set (modelling approach) and analysis of the further applicability of the model (qualitative approach). According to Morse (2003), "*by using more than one method within a research, we are able to obtain a more complete picture of human behaviour and experience which enables us to broaden the dimensions and hence the scope of the research project*". A three step approach was adopted in implementing the multi-method approach.

The first step introduces the research and followed up with a comprehensive literature review which included the collation of experimental data for the modification and validation of the model. The second step focused on the modelling component of the research which includes firstly; the modification of the underlining anatomic and thermo-physical properties of the original Fiala model to reflect that of the older person (passive system) based on data collated on older persons. Secondly; the use of a novel optimisation approach with the working principles of Genetic Algorithms (GA) to develop new sets of control equations for the central nervous system (active system) based on the available collated experimental data. After modifications were carried out, statistical analysis was undertaken to evaluate the predictive capability of the new Older Persons Model,

The third step involved the application of the model by the simulation of combinations of various environmental temperatures (test case scenarios) based on information extracted from published literature. A qualitative study involving semi-structured interview was also conducted to investigate the usability and usefulness of the model. Figure 1.4 shows the schematic diagram of the multi-method research methodology model adopted in carrying out the research.

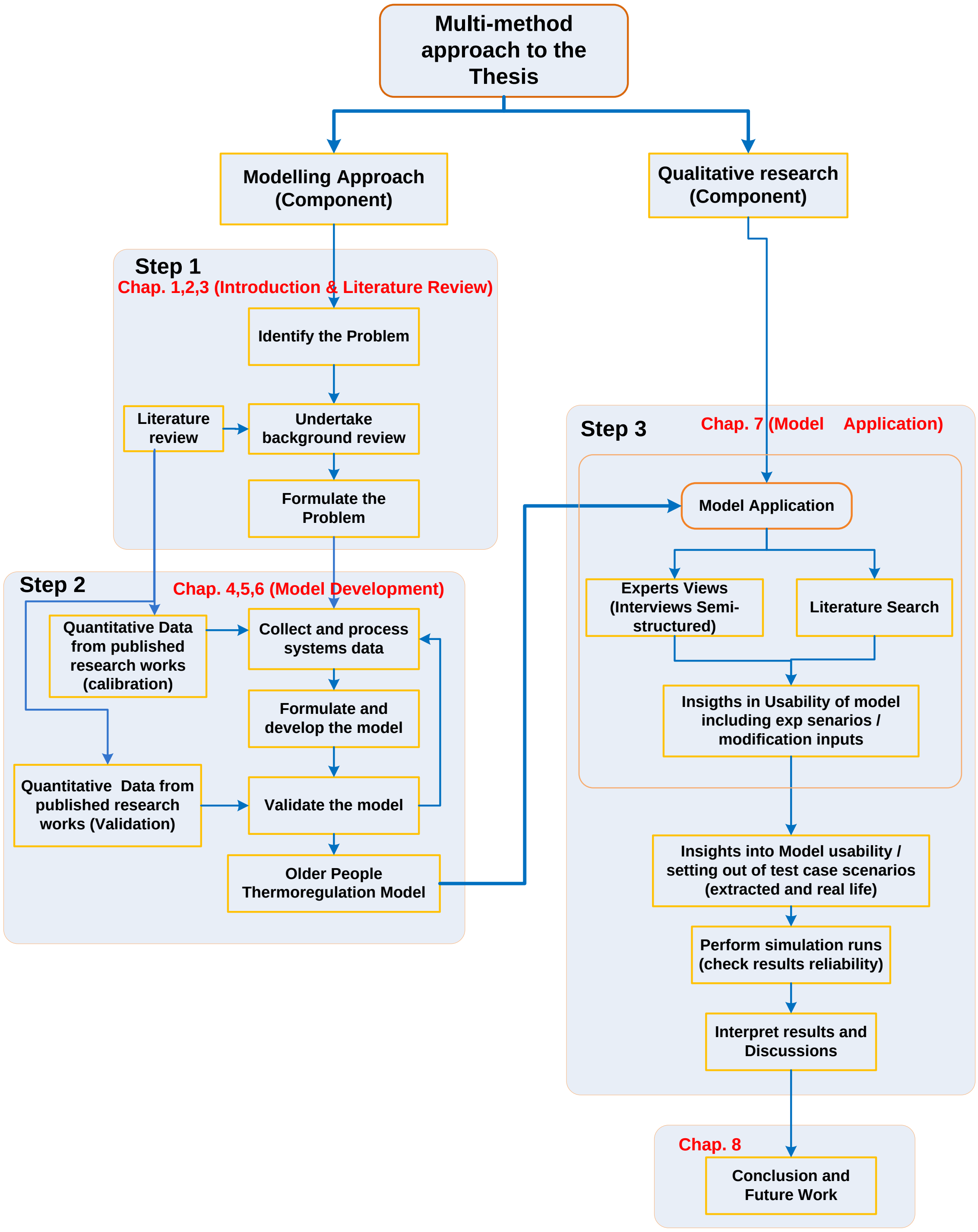

Figure 1.4 Multi-method research methodology model

1.14 Structure of the thesis

This thesis is structured according to the aims and objectives of the study and presented in 8 chapters and outlined in Table 1.1.

Chapter one introduces the background of the study as well as the main aim and individual objectives.

Chapter two focused on detailed review of relevant literature about the ageing statistics across the globe, human thermoregulation and physiology of thermoregulation. **Chapter three** presents a review of thermal comfort and modelling of thermal comfort with focuses on the major thermoregulation models. It also contained a detailed review and extended validation of the selected human thermoregulation model to be adapted.

Chapter four presents the steps adopted in designing the passive system of the Older Persons Model. These include the selection of a representative typical average age for older persons, the extraction of data relevant data for the typical older person, sensitivity analysis of major body parameters in the passive system and the verification of the passive system of the typical older person.

Chapter five presents the steps adopted in designing the active system of the Older Persons Model with focus on the rational for the modification of the active system to reflect that of the older persons, the methods adopted and the implementation of the selected method. The final sets of coefficients for the active system of the older person were reported in this chapter.

Chapter six presents the results of the verification and validation processes of the model development including analysis of statistical metrics used to evaluate the goodness of fit of the model to experimental data.

Chapter seven introduces the qualitative research component of this research with focus on the extraction of test case scenarios for the model application from literature and discussion of interview study results.

Chapter eight presents the conclusion and possible directions of further work.

Table 1.1 the Outline of the thesis

Chapter	Title	Method	Objective
1	**Introduction**	Outlining the overall research	Describing the research Scheme
2	**Aging and Human Physiology**	Undertaking Comprehensive Literature review	Exploring latest information and findings in the subject area
3	**Thermal comfort and Comfort Modelling**		
4	**Development of the Passive System**	Sensitivity analysis of body parameters, extraction and analysis of anatomical properties of older people	Determine the representative body parameters affected most by ageing for modification
		Performing modification procedure on the passive system of the thermoregulatory model	To modify the existing models passive system to resemble that of the older person
5	**Development of the Active system**	Collate, analyse, extract and use experimental data from published literature	To select the most relevant experiments to be used for modifying the active system of the existing model
		Performing modification procedure on the active system of the thermoregulatory model	To modify the existing models active system to resemble that of the older person
6	**Results and Analysis**	Carrying verification and validation simulations of test cases and calculating various statistical metrics	To determine the goodness of fit of the model and its predictive capability in terms of predicting the thermal behaviour of the older person
7	**Model Application**	Undertake Model Applications using various test case scenarios	To test the wider application of the model in varying conditions
		Carrying out interview study on further application of the model	To elicit feedback from professionals about the potential applications of the model
8	**Conclusion and further work**	Highlighting the research findings	Outlining the findings of the research
			Concluding and suggesting further work

Chapter 2

Ageing and Human Physiology

2.1 Introduction

This chapter reviews published findings on the population of the world with focus on the ageing of populations around the world. It also explores the basics of human thermoregulation looking at the heat balance of the body and the physiology of thermoregulation. Further review of literature was carried out on ageing and thermoregulation with focus on how older people response to heat and cold stress.

2.2 Ageing Demography

The population division of the United Nations has a long tradition of studying population ageing by estimating and projecting the size and characteristics of ageing populations around the world. One of its exhaustive reports titled 'World population Ageing 2009' presented some of the most detailed demographic composition of the World (UN, 2009)**.** The report underscored four major findings relating to population ageing around the world. These include:

- *"the pervasive nature of population ageing which is affecting all countries of the world" (UN, 2009),*
- *"the profound nature of the problem with its implications and consequences for human life" (UN, 2009),*
- *"the unprecedented nature of population ageing with the number of older persons (those aged 60 year or over) expected to exceed the number of children for the first time in 2025" (UN, 2009).*
- *"the enduring nature of population ageing since 1950 with older persons passing from 8 % in 1950 to 11% in 2009" (UN, 2009)* (Figure 2.1).

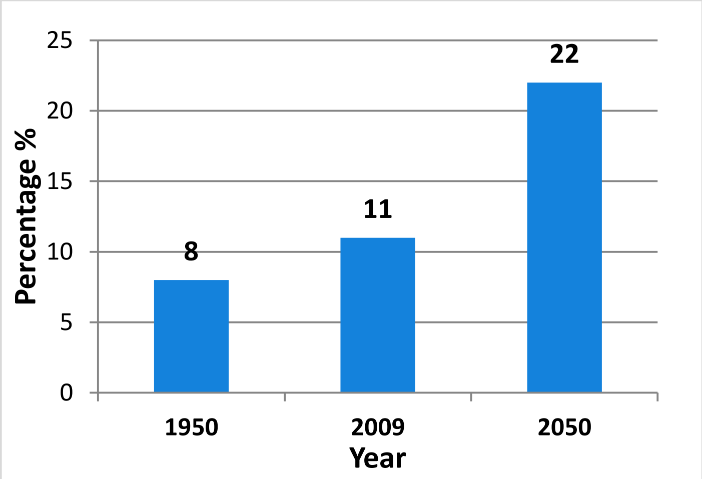

Figure 2.1 Proportion of population 60 years or over in the world 1950-2050 (UN, 2009)

The report points out that most developed region of the world have relatively high proportions of older persons. Furthermore, their populations are projected to remain considerably older than those of the developing countries as a whole. As of 2009, 21% of the population in the more developed regions of the world was aged 60 year or over, whereas for the less developed regions it was 8%. By 2050, in the developed regions of the world people aged 60 years or over are projected to be 33% with Europe being the area with the highest proportions of older persons compared to 20% in the less developed regions (UN, 2009). The proportion of populations aged 65 or over in Africa is projected to rise from 3% in 2009 to 7% in 2050.

One important phenomenon of this ageing rate is that the old-old (those aged 75 and over) are expected to make up 19.7 percent of the total population in 2030 and 24.9% in 2050. In Germany, Italy and Japan people aged 60 years and over currently constitute more than 25% of the population and in Japan, this rate is estimated to reach 31.8% in 2030 and 39.6% in 2050. In China, persons aged 60 year and over are noted to constitute a rapidly growing share of the populations (Figure 2.2). By 2050, the population is projected to have people aged 60 years and over and 80 and over to reach 440 million and 101 million respectively (UN, 2009).

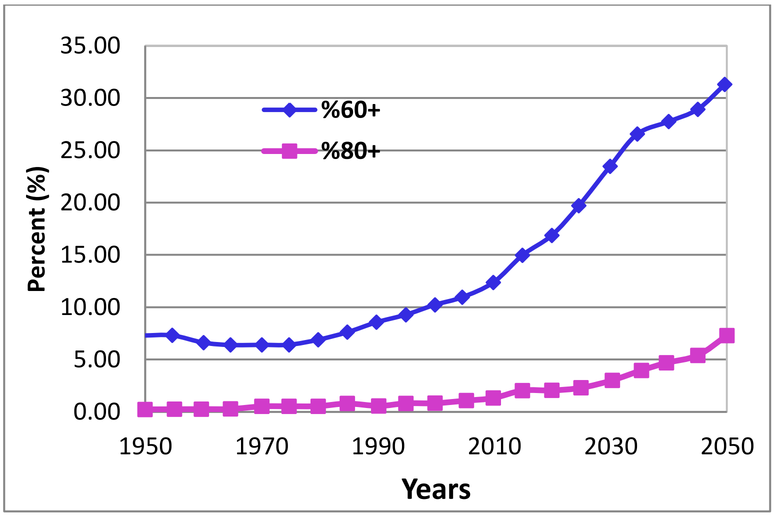

Figure 2.2 China's population ageing (UN 2009)

In the US, according to the Department of Health and Human Services report on the profile of older Americans 2008, persons aged 65 or older were more than 37.9 million in 2007 and represented 12.6% of the total population. In reality the older population is getting older and in 2007, the 65-74 age group was over 8.8 times larger than in 1900 whiles the 75-84 was 17 times larger and 85 and over was 45 times larger (AoA-USDHHS, 2008). The report points out that, a child born in 2006 could expect to live 78.1 years representing an increase of 30 years as compared to a child born in 1900. The older population on its own continues to grow significantly as shown in Figure 2.3. The population of people aged 65 years and over is likely to increase from 35 million in 2000 to 40 million in 2010 (15% increase) and then to 55 million in 2020 (36% increase) (AoA-USDHHS, 2008).

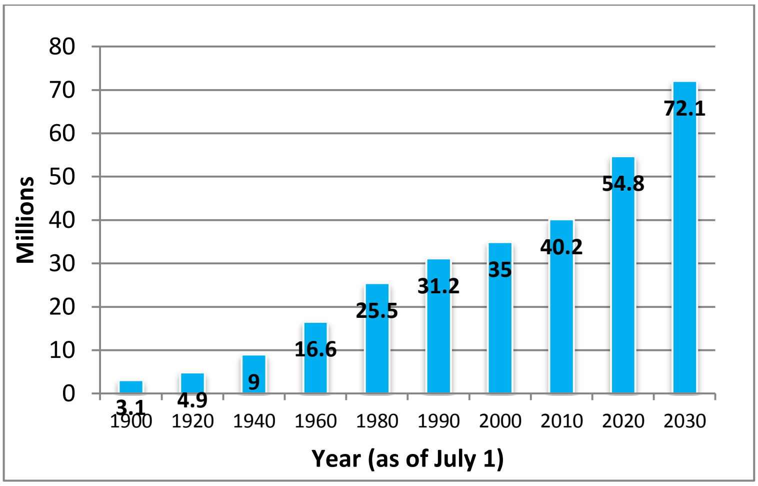

Figure 2.3 Number of persons 65+ (1900 – 2030 in millions) (AoA-USDHHS, 2008)

The population of the United Kingdom (UK) is also ageing. Over the last 25 years the percentage of the population aged 65 years and over increased from 15 percent in 1984 to 16 percent in 2009, an increase of 1.7 million people (ONS, 2010). Over the same period, the percentage of the population aged less than 16 decreased from 21 percent to 19 percent. This trend is projected to continue and by 2034, 23 percent of the population is projected to be aged 65 years and over compared to 18 percent aged less than 16 years. According to ONS (2010), the fastest increase in population are those aged 85 years and over who are referred to as the oldest old. Figures indicate that in 1984, the numbers of oldest old were around 660,000 people in the UK but since then, the numbers have doubled up to 1.4 million in 2009. The projection is that, by 2034 their number will account for 5% of the population which is 2.5 times more than in 2009 reaching 3.5 million (ONS 2010).

As in most region of the world, the French population continues to age and the proportion of the youngest age group is diminishing. In 2005, 20.9% of the population was aged 60 years and over and this is projected to increase (ILC, 2009). This clearly demonstrates that the ageing of population across the world is not restricted to geographical areas but an issue of concern to both developing and developed countries.

2.3 Human Thermoregulation

Human beings by the process of thermoregulation maintain a normal average body temperature of about 37°C even in the face of wide variations occurring in their day to day activities and the environmental temperature they are exposed to (Sherwood, 2010, Tortora and Derrickson, 2007b). The temperature of the human body at any given time can be referred to as the balance between the heat gained by the body and heat that is dissipated into the surrounding environments. Internal body heat is generated by oxidation of metabolic fuel resulting from food that is consumed (Sherwood, 2010)**.** This heat is carried by blood to the surface of the body (skin) which is then transferred to the environment. If the amount of heat production equals the amount of heat loss, the body maintains a nearly constant deep body temperature near 37°C (Tortora and Derrickson, 2007b)**.** Even though 37°C is widely accepted as the average body temperature, the temperature of the various regions of the body composed of different tissues, organs and systems varies from one another.

The brain and organs within the thoracic and abdominal cavities have a higher and a more constant temperature and are usually referred to as the core temperature see Figure 2.4 (Sherwood, 2010, Pocock and Richards, 2006). The temperature of the body surface including hands and feet are well noted to be lowest and referred to as the shell temperature see Figure 2.4 (Pocock and Richards, 2006, Sherwood, 2010). Depending on the activity level of the body and the environmental temperature it is exposed to, the core and shell temperature also referred to as the mean skin temperature vary. However, the shell temperature varies more widely than the core temperature. These two temperature readings (core and mean skin temperature) play a major role in the analysis of the physiological and thermal state of the human body.

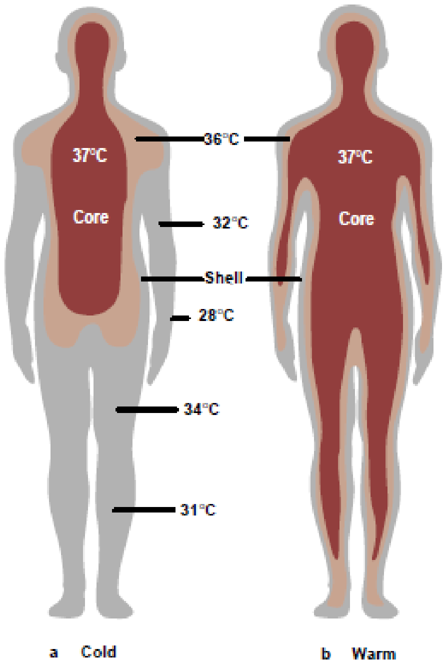

Figure 2.4 Illustration of core and shell temperature (Wenger, 2002)

Research has found that, the mean skin temperature and head core temperature affect regulatory responses and the rate of change of the mean skin temperature has been identified as a governing dynamic signal of thermoregulatory responses (Fiala et al., 2001).

2.3.1 Core Body Temperature

Wunderlich (1869) is credited with establishing the ranges of normal body temperature as (36.2°C to 37.5°C) in 1869 after the collection of auxiliary temperature of 25,000 healthy subjects and promulgating a normal average body temperature of 37°C (Lu et al., 2009, Kelly, 2006, Mackowiak et al., 1992)**.** Wunderlich was reported to have found lower readings of (0.5°C) in older people as compared to adults of a younger age (Lu et al., 2009). Pocock and Richards (2006) states that, when temperature is measured in the mouth (oral temperature), 95% of people fall within the range of 36.3 to 37°C. Most people's body temperature vary during the day ranging from the lowest reading in early morning (around 4 am) to the highest in the late evening (Pocock and Richards, 2006). Whilst 37°C has been widely adopted and used over the years, some researchers have questioned the accuracy of the thermometer used by Wunderlich in

1869 in relation to the current modem thermometry which has improved accuracy. Lu et al.(2009) reports that, work done by Mackowiak & Worden in 1994 show that, the thermometer used by Wunderlich read (1.4°C to 2.2°C) higher than the thermometry in use today. Mackowiak (1992) carried out a critical appraisal of the normal body temperature 37.0 °C, involving 148 healthy men and women and found values which conflicted with that of Wunderlich and suggests 36.8°C rather than 37.0°C as the mean oral temperature.

To determine the core body temperature, various sites of the body are used and these include the rectum, oral, axilla (under the armpit) and sometimes the urine. Each of these sites gives a representative value of the body temperature but variations exits between sites. Sherwood (2010) points out that, rectal temperature averages about 0.56°C higher than the oral and axilla. Rectal site measurement is considered closely reflecting the core body temperature of a person but sources of error can result from excess faecal matter and inadequate insertions of the thermometer to a reasonable depth (Lu et al., 2009). The oral cavity is also one of the most popular sites used for the measurement but error can occur as a result of the temperature of the beverages taken by the person. Another source of error could be the difficulty in keeping the probe in one place in the mouth and keeping the lips sealed (Lu et al., 2009). Urine temperature can be measured using indwelling urinary bladder thermistor but the method is considered intrusive and mostly used for patients who are critically ill. Axillary site measurement does not carry the problems of body fluid as in the case of the rectal, oral and urinary but they usually lag behind the core temperature and sometimes less accurate and reflecting skin rather than core body temperature (Lu et al., 2009). Tympanic membrane is also used because convenient and sometimes researchers use the esophageal temperature measurement which is relatively closer to the oral temperature (Lu et al., 2009). Whilst all the sites of temperature measurement have various degrees of variations in the temperature reading, ageing of the human body also have effect on temperature readings from the various site of the body.

2.3.2 Core Temperature in older persons

Older people are noted to have average lower body core temperature sometimes around 36.4°C (Sherwood, 2010). Güneş and Zaybak (2008) carried out an experiment measuring the axillary body temperature of 133 older people in a nursing home using mercury in glass thermometer and found that, the mean axillary temperature of the older people examined ranged from 35.1°C to 36.4°C. They concluded that, older people have a mean axillary body temperature lower than 36.5°C. A systematic review of body temperature variations in older people carried out by Lu et al.(2009) reveals that in three studies measuring 547 rectal temperatures, the normal rectal temperature was found to be 37.1°C and the range was 37.0°C to 37.2°C. In five studies where 1,118 ear based temperatures were collected, the normal tympanic temperature was found to be 36.7°C and the range was 36.4°C to 37.3°C. They also reviewed four studies which collected 1282 urine temperatures with the normal urine temperature found to be 36.5°C with a range of 36.3°C to 36.7°C.

Normal oral temperature was found to be 36.3°C of 2,265 measurements with the range being 36.1°C to 36.6°C. Across 395 axillary measurements, the normal axillary temperature was found to be 36.2°C and the range being 35.7 to 36.6°C. Table 2.1 shows the comparisons of the statistics of elderly body temperature (Lu et al., 2009), whilst Table 2.2 shows the comparisons of mean temperature of adults and the elderly.

Table 2.1 Comparisons of the statistics of elderly body temperature

	Sites	**Mean (°C)**	**Range (°C)**	**Difference (°C)**
Sites	Rectal	37.1	37.1-37.2	
	Ear-based	36.8	36.4-37.3	0.3 Lower than rectal site
	Urine	36.5	36.3-36.7	0.6 Lower than rectal site
	Oral	36.3	36.1-36.6	0.7 Lower than rectal site
	Axillary	36.2	35.7-36.6	0.9 Lower than rectal site
Diurnal Variations	Morning	36		
	Afternoon	36.4		
Circannual Variations	Summer	36.4		
	Winter	36.3		

Table 2.2 Comparisons of mean temperature of adults and elderly

Sites	**Mean Body temperature Adult (°C)**	**Mean Body temperature Elderly (°C)**	**Difference (°C)**
Rectal	37.5	37.1	0.4 lower than adult
Ear-based	37	36.8	0.2 lower than adult
Oral	37	36.3	0.7 lower than adult
Axillary	36.5	36.2	0.3 lower than adult

2.3.3 Mean Skin Temperature

Mean skin temperature is an important physiological parameter which reflects human response to thermal stimulus and states of heat exchange between that human body and the thermal environment (Liu et al., 2011). But in reality its measurement is a difficult process due to local temperature variations in the skin (Vanos et al., 2010). Mitchell and Wyndham (1969) highlights the importance of accurate measurement of mean skin temperature stating that it constitutes an important parameter in the study and analysis of human beings response to his/her thermal environment. Under thermo-neutral conditions, mean skin temperature varies within the range of 32°C to 34°C. Many authors and investigators have proposed various formulas for use in determining the appropriate mean skin temperature. According to Choi (1997), the true mean skin temperature can only be measured by obtaining an unlimited number of measuring sites of temperature on the skin but concedes that is virtually impossible to determine the skin temperature over the entire body surface. As a result authors and investigators generally limit the determination of the mean skin temperature to a finite number of skin temperature and their corresponding weighting factors (Mitchell and Wyndham, 1969, Choi et al., 1997). To obtain the value for the mean skin temperature, a number of local skin temperatures are summed up with their corresponding weighting factors.

The general formula widely used for the estimation of the mean skin temperature (T_{skm}) is

$$T_{skm} = f_1 * T_1 + f_2 * T_2 + \ldots\ldots f_n * T_n \tag{2.1}$$

Where $T_1, T_2 \ldots\ldots T_n$ are the local skin temperatures and $f_1, f_2 \ldots\ldots f_n$ are the corresponding weighing factors also referred to as the weighting coefficients. Weight coefficients are the fraction of the local body area having the temperatures of

$T_1, T_2 \ldots\ldots T_n$ (Mitchell and Wyndham, 1969, Choi et al., 1997). Many formulas with various numbers of skin temperature sites have been proposed with the number of sites varying from 3 to 15 (Choi et al., 1997). Burton in 1934, proposed a simple mean skin temperature formula with three skin temperature measurements equations 2.2 (Ramanathan, 1964)

$$T_{skm} = 0.5_{trunk} + 0.36_{leg} + 0.14_{lower\ arm} \tag{2.2}$$

Ramanathan (1964) proposed a mean skin temperature formula with four skin temperature measurements

$$T_{skm} = 0.3_{chest} + 0.3_{arm} + 0.2_{thigh} + 0.2_{leg} \tag{2.3}$$

Hardy-Dubois proposed a mean skin temperature formula with seven skin temperature measurements (Ramanathan, 1964)

$$T_{skm} = 0.35_{trunk} + 0.19_{thigh} + 0.14_{\ arm} + 0.13_{leg} + 0.07_{head} + 0.07_{foot} + 0.05_{hand} \tag{2.4}$$

Colin/Houdas 10 points mean skin temperature formula sourced from (Yao et al., 2007)

$$T_{skm} = 0.06_{tskA} + 0.12_{tskC} + 0.12_{tskE} + 0.12_{tskM} + 0.08_{tskD} + 0.06_{tskF} + 0.05_{tskG} + 0.19_{tskH} + 0.13_{tskJ} + 0.07_{tskK} \tag{2.5}$$

Mitchell and Wyndham (1969) 15 points mean skin temperature formula

$$T_{skm} = \frac{1}{15}\sum(t_{sk}, A + t_{sk}, C + t_{sk}, D + t_{sk}, E + t_{sk}, F + t_{sk}, G + t_{sk}, H + t_{sk}, J + t_{sk}, K + t_{sk}, L + t_{sk}, M + t_{sk}, N + t_{sk}, P + t_{sk}, Q + t_{sk}, R) \tag{2.6}$$

Mitchell and Wyndham (1969) in their work on comparison of weighting formulas for calculating mean skin temperature concluded that, the 15 sites measurement formula appear to constitute a reasonable maximum. However, Liu et al. (2011) in evaluating the calculation methods of mean skin temperature for use in thermal comfort study reviewed the predictions of 26 types of mean skin temperature calculation ranging from 3 to 17 temperature sites measurement. They suggest 10 sites formula as the most appropriate for the mean skin temperature due to its high reliability, excellent sensitivity and fewer measuring sites. These studies reveal the complexities associated with measuring of mean skin temperature in contrast to the core temperature. The different approaches proposed by various authors have their own pros and cons and no two approaches produce the same results. Figure 2.5 shows the various sites for skin temperature measurement.

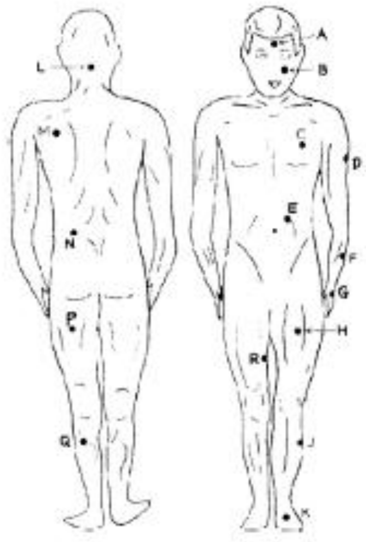

Figure 2.5 Sites of skin temperature measurement

Where; (A) forehead, (B) face, (C) chest, (D) upper arm, (E) abdomen, (F) foreman, (G) back of hand , (H) anterior thigh, (J) anterior leg, (K) back of foot, (L) neck, (M) back, (N) lumber, (P) posterior thigh, (Q) posterior leg, (R) side of thigh (Liu et al., 2011)

2.4 Body Heat Balance

Human beings like other mammals consume food which is then converted into energy for use of the body. For the body to stay healthy and thermally balanced, body heat both generated internally and sometimes acquired from the environment such as solar radiation must be balanced by heat that is lost to the environment. Heat production is predominantly determined by the metabolic activity of the body which is required to perform activities. Most of the energy used by the body is released as heat and there are several routes through which this heat is lost from the body as shown in Figure 2.6.

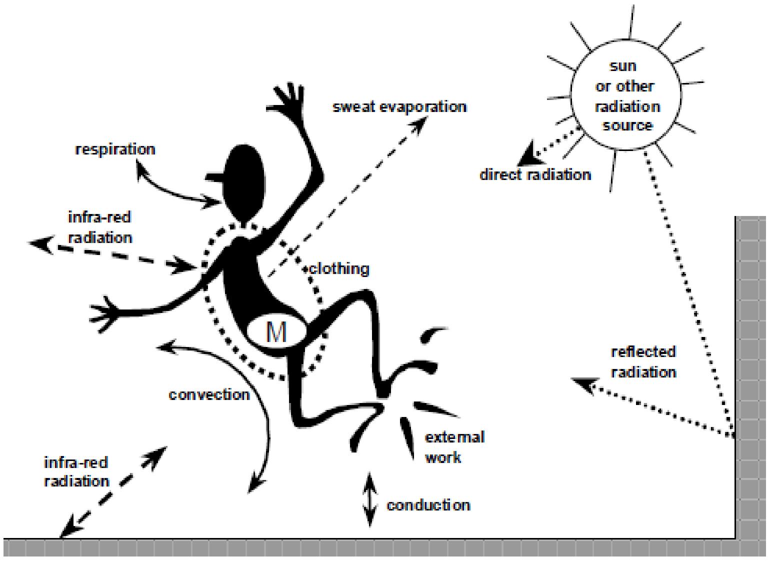

Figure 2.6 Heat loss and gain routes (Havenith, 1999)

Heat loss from the body to the environment is reliant on the body surface area that is involved (Figure 2.6) and the clothing insulation in conjunction with the driving force of temperature or vapour pressure gradient (Havenith, 2005). Before the human body temperature can be said to be stable, heat losses need to balance heat production if not the heat content of the body will change, causing the body temperature to rise (positive storage) or fall (negative storage). Body heat balance can therefore be written as; (Havenith, 1999).

Store = Heat production – heat loss
= (Metabolic rate – external work) – (Conduction + Radiation + Convection + Evaporation + Respiration) (2.7)

The human body loses heat by Conduction (contact with solids, such as floors) However heat loss by Convection is when heat is transferred from the body to the air around it by the flow of (cool) air across the skin. Heat loss by Radiation can also be substantial and occurs when there is a difference between the body's surface temperature and the temperature of the surface in the environment. Evaporation is the transfer of water from its liquid from to vapour form. Due to the human body's ability to release sweat in response to increased heat gain, when the moisture appearing on the skin is evaporated, large amounts of heat can be dissipated from the body. The lungs of the human body are also involved in the heat loss process in that, as inspired air is usually cooler and dryer than the lungs internal surface, by warming and moisturizing the inspired air, the body losses an amount of heat in the expired air by Respiration which can be up to 10% of total heat production (Havenith, 2002).

2.5 Physiology of Thermoregulation

Thermoregulation refers to the mechanisms and control systems used by the body to balance thermal inputs and thermal losses so as to maintain its core temperature nearly constant (Thompson-Torgerson et al., 2008b, Laberge, 2002). Like many physiological control systems, it relies on multiple levels of positive and negative feed-back to minimize deviations from the normal status (Kurz, 2008). Human body temperature is regulated by signals that are derived from tissues in the body including the brain (hypothalamus), the spinal cord and the skin (Kurz, 2008, Zhou, 1998). Due to the effectiveness of the human body's regulatory system, the core body temperature is kept at approximately 37°C. The thermoregulatory system functions as a feedback control system with a reference or set temperature (Adair and Black, 2003). In the event of deviations occurring between the integrated signal and the set point the appropriate thermal response is triggered by the central nervous system.

The major components of this system are the thermo receptor (sensors), the central controller and the effectors. The processing of multiple thermoregulatory signals from various tissues in the body occur in three phases which are: afferent thermal sensing by temperature sensitive neurons, central regulation, and efferent responses (Kurz, 2008). Figure 2.7 shows the schematic diagram of the thermoregulatory system showing the thermo receptors (cold and warmth), the afferent pathway- the pathways through which afferent signals pass to the central nervous system (CNS) which serves as the core thermal receptor, the efferent pathways, the effectors and the hypothalamus which is the dominant thermoregulatory control centre in mammals (Sessler, 2008).

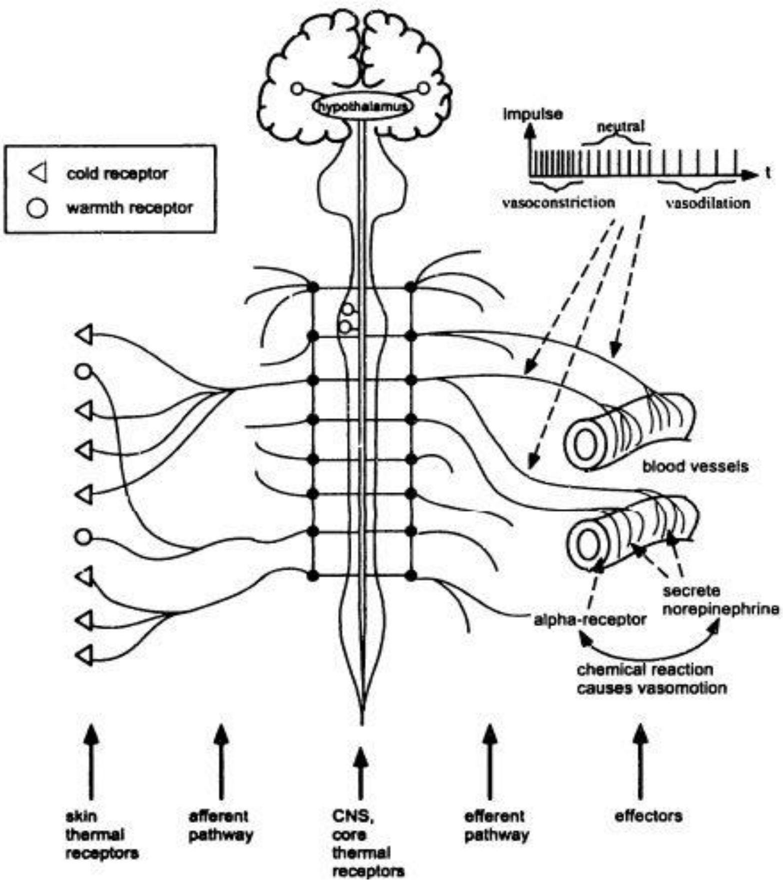

Figure 2.7 Schematic of the thermoregulatory system (Zhou, 1998)

Hypothalamus serves as the body's thermostat which receives afferent information about temperature variations in the body regions by way of cold and warm thermo receptors (Sherwood, 2010). Cold signals pass through A delta (Aσ) fibres where warmth signals pass through C fibres (Kurz, 2008). Cold receptors increase their activity when tissue cools and heat receptors increase their activities when tissue heats up. Cold receptors found mostly in the skin have a peak rate of discharge of impulses at 25-30°C and warm receptors have a maximal discharge rate at 45-50°C (Buggy and Crossley, 2000). The signals from the receptors are received by the central control mechanism in the hypothalamus which determines the mean body temperature by integrating it and comparing it with a predetermined set point or threshold (Adair and Black, 2003). An output command is generated to energize an appropriate response whenever a load error occurs (Adair and Black, 2003). Figure 2.8 shows the hypothalamus where inputs from the skin surface, deep abdominal and thoracic tissues, spinal cord, and portions of the brain are integrated (Kurz, 2008).

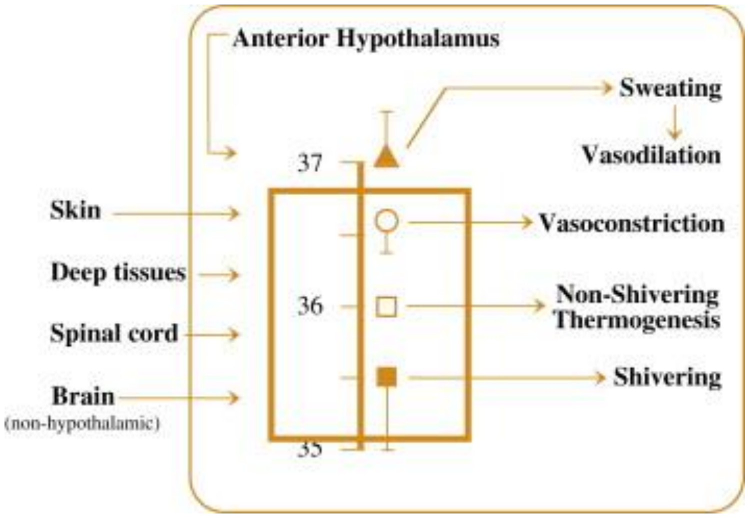

Figure 2.8 Schematic diagram of the hypothalamus (Kurz, 2008))

The load error resulting from the integration of the signals could be negative or positive and this is characterized by behaviour alteration and vasomotor responses (Buggy and Crossley, 2000). A negative load error (for example the body temperature is lower than the set point or less than cold-response thresholds) the output command will increase heat production (i.e. vasoconstriction and shivering). In the event of a positive load error (temperatures exceeding warm-response thresholds) the command will increase heat loss (i.e. sweating) (Adair and Black, 2003). Temperatures between sweating and vasoconstriction thresholds define the inter-threshold range which is normally 0.2°C (Kurz, 2008). Within this range the bodies' thermoregulatory responses are found to be dormant (Sessler, 2008).

The particular effector response that the thermoregulatory system mobilizes in relation to its strength depends to a large extent on the prevailing environmental temperature (Adair and Black, 2003). Whilst the normal core body temperature in humans typically range between 36.5 to 37.5°C values far less than 36°C or higher than 38°C usually indicate loss of control of the thermoregulatory control due to extreme thermal environment (Sessler, 2008). Table 2.3 shows the effects of extreme heat or cold on the body.

Table 2.3 Temperature effects on the body (Pisacane et al., 2007)

Condition	Temperature °C	Symptoms
Heat stroke	>44	Brian death certain
	41-44	Includes all symptoms of heat exhaustion plus disfunction of central nervours system causing altered mental state, disorinetation, strong rapid pulse, coma, and begining of brain death
Heat exhaustion	39-41	Fatigue and weakness, nausea and vomiting, headache, muscle cramps, irritability and raised pulse
Heat Cramps	38-39	Painful muscle spasms with pulse normal or slightly elevated, often caused by salt depletion
Normal	**36-38**	**Normal**
Mild Hypothermia	35-36	Cold sensation, goose bumps, lack of some hand coordination, shiver can be mild to severe
Moderate Hypothermia	34-35	Intense shivering, apparent lack of muscle coordination, movements laboured, mild confusion but appears alert
	32-34	Voilent shivering, difficulty speaking, lack of some cognitive functions, muscle stiffness, sign of depression
Severe hypothermia	30-32	Shivering stops, incoherence, poor muscle coordination, irratinal and confused, inability to walk
	28-30	Muscle regidity, semi-consiousness, pulse and respiration decrease, pupil dilation, desire to sleeep, possible heart fibrillation
	26-28	Unconscious, muscle failure, pulse and heart rate erratic, respiratory failure, possible death
	<26	Pulmonary edema, cardiac and respiratory failure, Death.

Figure 2.9 shows the major pathways through which the human body attains its thermal balance by way of thermoregulation (Sherwood, 2010). It can be observed that a change in the skin temperature is sensed by thermo receptors in the skin whilst a change core temperature is sensed by thermo receptors in the hypothalamus and deep core organs. These changes are then integrated in the hypothalamus which compares it with the set point temperature to initiate the appropriate response. In hot conditions, signals from the sympathetic nerves move to the sweat glands for sweat to be generated which leads to dissipation of heat accumulated in the body. In individuals who are conscious, modification of behaviour can be more powerful that the autonomic mechanisms of regulating body temperature (Buggy and Crossley, 2000).

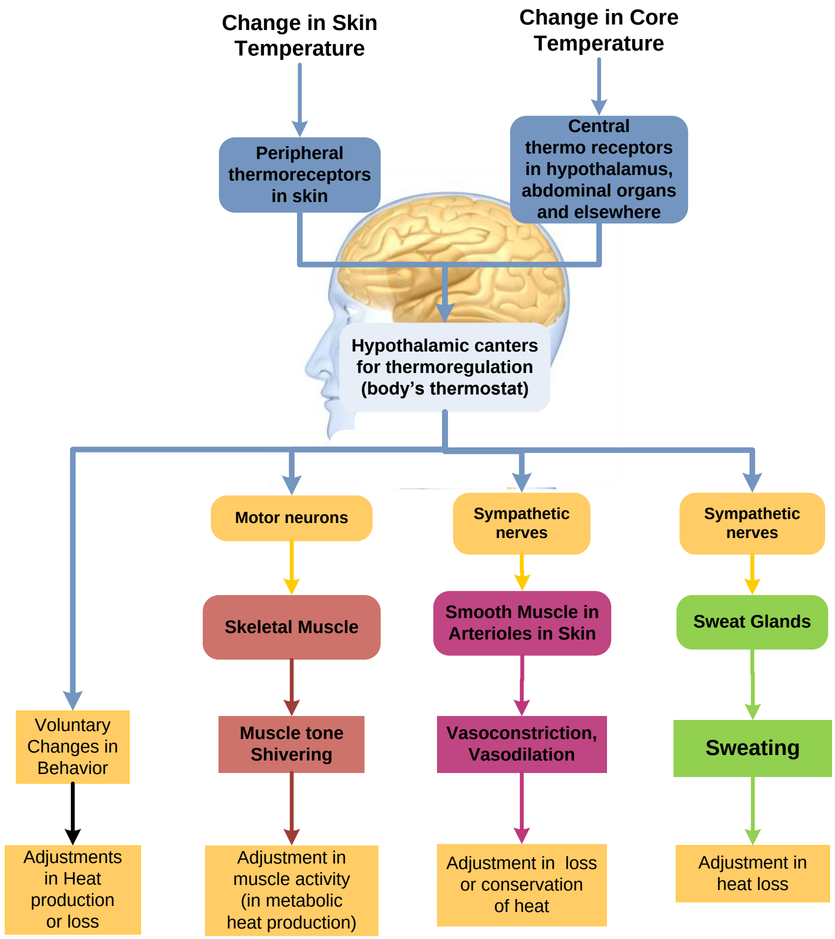

Figure 2.9 The major pathways of human body thermoregulation (Sherwood, 2010)

2.6 Thermoregulatory response to cold

When the human body is exposed to cold conditions leading to a fall in its core temperature, the body initiates homeostatic (physiological) responses to reduce the heat that is being lost to the environment and also generate heat internally by vasoconstriction and shivering respectively. Vasoconstriction involves the contraction of blood vessels and decrease of blood flow to the extremities of the body including the hands and feet leading to reduction in the heat loss from the skin surface. This is to maintain a near constant normal temperature of 37°C in the vital organs. When vasoconstriction is inadequate to prevent heat loss, metabolic heat productions is increased by shivering (Pocock and Richards, 2006). Shivering, appears to be a last resort response to extreme cold and consist of rhythmic, oscillating skeletal muscle contractions that occur at rapid rates of 10 to 20 per second (Sessler, 2008). This is very effective in increasing the human body's heat production (Sherwood, 2010). Shivering is a specialized form of muscular activity in which the muscles themselves perform no external work and virtually all the energy of contraction is converted directly to heat (Pocock and Richards, 2006). Sustained shivering augments metabolic heat production 50 to 100 percent in adults (Sessler, 2008).

Figure 2.10 shows the illustration of vasoconstriction and shivering response to core temperature deviation from set point as a result of heat loss. Even though shivering produces considerable heat which helps the body to maintain reasonable core temperature in exposures to cold, it may not be able to keep producing more heat in situations of long exposure (Pocock and Richards, 2006). As such, humans adopt other measures including behavioural thermoregulation in order to reduce heat lost from the body. Sessler (2008) defines behavioural thermoregulation as the intentional manipulation of heat exchange with the environment which allows humans to live in the warmest and coldest climates on earth and one of the most powerful thermoregulatory responses. Behavioural responses are most often initiated before autonomic responses (Blatteis, 2012). For behavioural responses to fall in the core temperature, people will seek warmer environments, increase their clothing insulation, take in warm fluids or change their posture which involves manoeuvres such as hunching over, clasping of arms on the chest or curling like a ball (Sherwood, 2010).

2.7 Thermoregulatory response to heat

When the human body is exposed to hot conditions leading to a raise in its core temperature, the body initiates homeostatic (physiological) responses to dissipate the accumulated heat to the environment by means of vasodilation and sweating. Vasodilation involves the dilation of the skin blood vessels and increase in the cutaneous blood flow. When maximal skin vasodilation is inadequate to dissipate excess heat from the body, sweating response commences to accomplish further heat loss through evaporation (Sherwood, 2010). Sweat is produced by eccrine glands with each person having about 2.5 million and about half situated in the dermis of the back and chest and is usually initiated at an ambient temperature of between 30-32°C (Pocock and Richards, 2006). Sweating is the only mechanism by which the body can dissipate heat in an environment exceeding core body temperature and is remarkably effective with each gram of evaporated sweat leading to a dissipation of 0.58 kcal of heat (Sessler, 2008). During evaporation of sweat from the skin surface, the heat required to transform water from a liquid state to a gaseous state is absorbed from the skin, thereby cooling the body (Sherwood, 2010). Therefore in order for sweat to effectively contribute the heat loss process of the body, it must be evaporated, sweat which drips off without evaporating contributes nothing to heat balance (Sessler, 2008).

Figure 2.10 shows the illustration of vasodilation and sweating response to core temperature deviation from set point as a result of heat gain. Humans adopt other measures including behavioural thermoregulation in order to facilitate heat lost from the body such as the reduction in clothing insulation, activity level and drinking cold beverages. Contrary to popular belief, wearing light-coloured, loose clothing makes you feel cooler than being naked, since naked skin absorbs all radiant energy that it is exposed to whereas light-coloured clothing reflects almost all the radiant heat that falls on it (Sherwood, 2010).

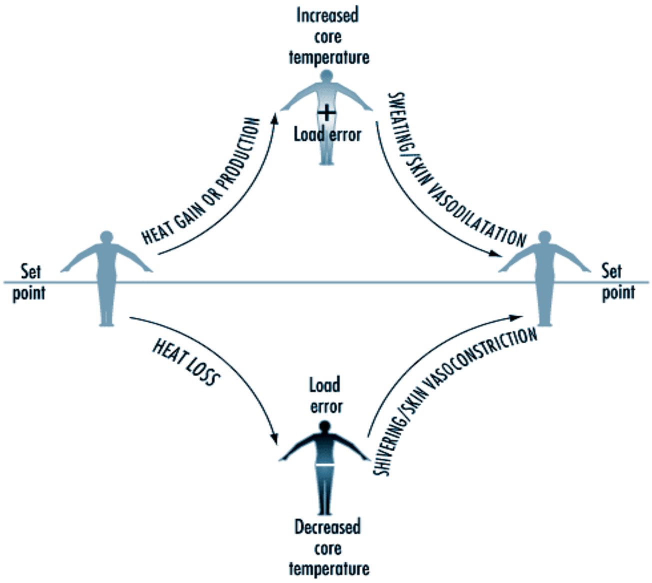

Figure 2.10 Vasodilation, sweating, shivering and vasoconstriction response (Kenney, 2012).

2.8 Ageing and thermoregulation

Thermoregulation in older adults is affected by age-related changes and is further compromised by other risk factors (Miller, 2012) including, disease, drugs and frailty and in some cases alcohol. In exposure to heat it has been found that the reflex cutaneous vasodilator response is reduced in the aged (Blatteis, 2012). Loss of skeletal muscle in the human body as a result of ageing known as sarcopenia and age related changes in the body composition and size may ultimately impact body temperature and thermoregulation in both hot and cold environments (Kenney et al., 1995). In addition, the ability to maintain core temperature of the inner body tissues within a narrow range is also reduced in old age as found out by Anderson et al. (1996). In their experiment looking at the passive temperature liability of the elderly, young and old subjects were heated by exercise, then cooled by immersion in a 28°C water bath thus maintaining a constant skin temperature.

In the healthy adult person the core temperature null zone defined as the range between the thresholds of shivering and sweating was found to be 0.43°C with an average core temperature of 37.1°C whiles in the elderly it was widened to 1.12°C with an average core temperature of 36.7°C. The widening of this null zone in older age may in some instances be responsible for a greater elevation of body temperature on exposure to heat and a greater fall on exposure to cooling (Appenzeller et al., 1999). In fact behavioural thermoregulation which is also one of the major responses to change in the thermal balance of the body is affected in the elderly and may probably be as a result of the weakening of the peripheral thermo sensitivity (Blatteis, 2012).

2.9 Ageing and Heat stress

Older people are more vulnerable to heat because of intrinsic changes in their regulatory system and sometimes as a result of the presence of drugs in their body which interferes with normal homeostasis. As a result, they may largely not be aware that they are becoming ill from high temperature so as to take action to reduce the exposure (WHO-Europe, 2004). Moreover, with advancing age, structural and functional changes occur in the peripheral blood vessels affects older person ability to cope with heat stimulus (Farage et al., 2010). Pierzga et al. (2003) found reduced skin blood flow response in older men in exposure to heat stress. Inbar et al. (2004) also found that ageing affects heat gain and heat dissipation capabilities of the older person. A study conducted by Anderson et al. (1996) found a link between age and reduced peripheral thermo sensitivity which affects older persons ability to effectively manage core temperature deviations when exposed to thermal stress. A further study conducted by Sagawa et al. (1988) to test the sweating and cardiovascular responses of aged men to heat exposure, found reduced arm blood flow to heat in older persons.

Dufour and Candas (2007) carried out an extensive investigation into ageing and thermal response in heat exposure where subjects' thermal detection threshold was measured at 9 different locations on the body (hand, forehead, upper arm, foot, calf, thigh, abdomen, chest, fore arm). Results from the study show reduction in thermal sensitivity of older and middle-aged subjects with associated increase in core and skin temperature but not in young subjects. The study also confirms a link between reduced sweat output and age. A further study by Kenney and Munce (2003) found reduced cardiac output, decreased skin blood flood and attenuated responds of individual sweat gland outputs in older individuals. Many other investigations both pharmacological and laboratory have been carried out to know more about the intrinsic link between reduction in sweat output in older people and the number of active sweat glands. Anderson (1987) found that the reduced sweat output in older persons was not linked to reduction in the number of sweat glands but as a result of the reduced amount of sweat produced by each gland.

Inoue (1996) conducted a longitudinal experiment in which subjects were re-tested after 5 years and found significantly greater increase rectal temperature in the second test than in first. The temperature threshold for the onset of sweating was also found to have increased. The test also found that the reduced sweat output was as a result of a lower sweat gland output per gland but not from the recruitment of fewer glands (Inoue, 1996). Kenney and Fowler (1988) injected concentrations of acetyl-beta-methylcholine chloride into the skin of the dorsal thigh to induce sweat generation. The activated sweat glands were photographed at 30 seconds intervals for 8 minutes. The study found reduced rate of sweat gland output per active gland in the older group. Another significant sweat gland output investigation was carried out by Hellon (1956) on 12 young students (18 and 23 years) and 12 college servants (45 and 57 years). In this investigation, subjects sat for 65 minutes, worked for 20 minutes and sat for the last 65 minutes of exposure. The work performed was stepping up and down from a stool twelve times a minute. Results show differences in sweat response patterns where young subjects began sweating at 15minutes into the test whilst older subjects began sweating at 29 minutes.

Futhermore, Buono et al. (1991) divided forty male volunteers into four subgroups of ten subjects each for testing. The groups include older trained (been exercising vigorously for at least the last 23 years), older untrained (were sedentary for at least the last 18 years), younger trained (exercised regularly for at least the last 3 years) and younger untrained (were sedentary for at least the last 6 months). Peripheral sweat production was induced via pilocarpine iontophoresis on the flexor surface of both forearms. Sweat was harvested for 15 to 20 min immediately after iontophoresis. The study found a 47% lower mean peripheral sweat rate in older subjects compared to the younger subjects. Buono et al. (1991) concluded that, the data supports the contention that ageing reduces the sensitivity of the human sweat gland.

2.10 Ageing and Cold Stress

Several experimental studies have been carried out using surveys and controlled laboratory investigations to determine how ageing impairments affect the performance of the elderly person’s body in cold stress. Horvath (1977) studied hypothermia in the aged and concluded that, temperature regulation following exposure to cold environment appears to be modified in elderly persons. Peripheral vasoconstriction is well noted to be an early physiological response to cold air exposure which minimizes heat flux from the body core to the air and the limbs play a vital role in this process. A related study by Kenney (1996) found that, older men vasoconstricted their limbs to a lesser extent than younger men.

Kenney and Munce (2003) also found reduced peripheral vasoconstriction and decreased metabolic heat production in older person during cold stress. Inoue et al. (1992), matched young (20-25 years) and old subjects (60-71 years) for body fat and surface area to mass ratio and exposed them to air temperature of (17°C and 12°C). During the experiment significant decreases in the core and skin temperatures of the older group were recorded in contrast to the younger group. DeGroot and Kenney (2007) investigated the impaired defence of core temperature in aged humans during cold stress and results of the study show that shivering response occurred at a lower core body temperature in the elderly. Frank (2000a) conducted an experiment involving 8 younger subjects (18-23 years) and 8 older (55-71 years) looking at age-related thermoregulatory differences during core cooling in humans. Results show that older subjects have a significantly lower core temperature threshold for vasoconstriction and heat production responses than their younger subjects. To test the influence of ageing on the thermoregulatory efficiency of man in cold stress, Mathew (1986b), exposed test subjects to a thermo-neutral environment of 27°C for an hour and later a cold test of an ambient temperature 10°C. Results of the experiment show a comparatively poor cold tolerance and thermoregulatory efficiency in elderly people. Collins et al. (1985) studied the effects of age on the body temperature and blood pressure in cold environments by exposing 4 young adults and 5 old men (63-70 years) to a still air of 6°C for 2 hours. Results indicate that; mean deep body temperature fell by 0.4°C in the old men and only by 0.1°C in the young adults. Collins (1985) therefore concluded that blood pressure elevation in cold was slower but more marked in the older person than the young adults.

2.11 Other Risk factors

Normal age-related changes in the body are often made worse by the presence and occurrence of chronic diseases. In reality chronic diseases are facts of life as the body grows old with many individuals having long standing chronic illnesses. These illnesses which are sometimes carried into old age include diabetes, hypertension and arthritis just to mention a few. People with some of these underling health illnesses may already have problems with their body organs due to the deterioration caused by these illnesses. As these illnesses manifest in the older person, the need to undergo treatments leads them to consume multiple medications which has a negative effect on thermoregulation (Havenith, 2001a). Drugs may also cause hypothermia by depression of the thermoregulatory set point or prevention of heat conservation (Cuddy, 2004). Also drugs can cause the temperature of the body to raise by fever from the pharmacologic action of the drug, drug administration fever and hypersensitivity reactions (Cuddy, 2004). Figure 2.11 shows an illustration of ageing effect on the thermoregulatory functions of the older people, response patterns and the negative functional consequences.

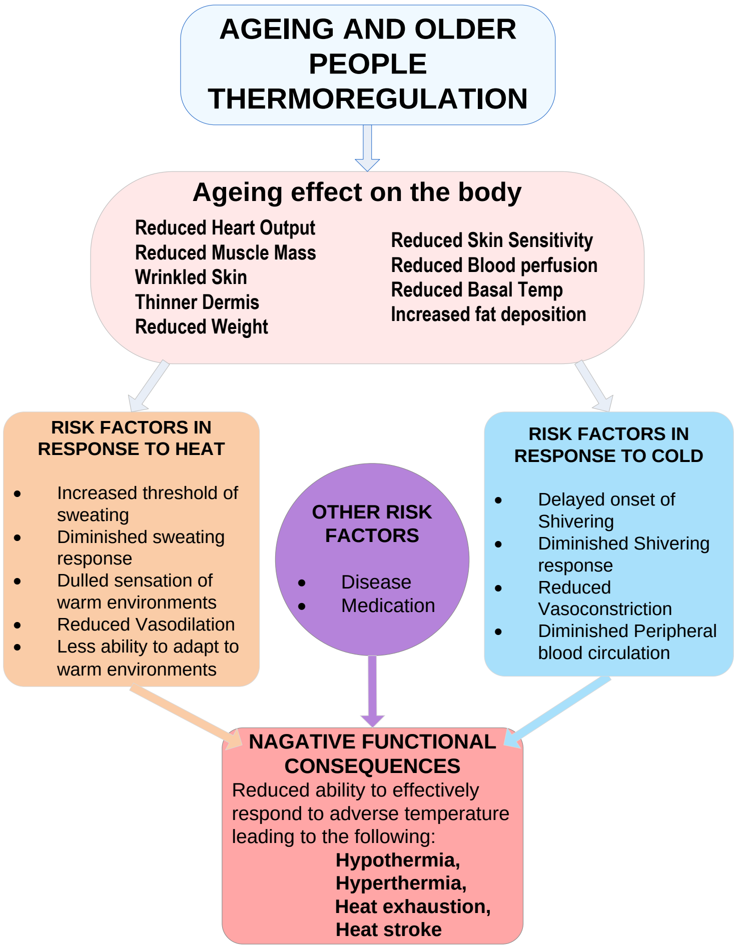

Figure 2.11 Ageing effect on the thermoregulatory functions of the older people

2.12 Summary

This chapter reviewed literature on the ageing of population's across the globe, the basics of human thermoregulation looking at the heat balance of the body and the physiology of thermoregulation. It also presents information related to the effect of cold and heat stress on the older person. Chapter 3 proceeds with the review of literature on thermal comfort, its predictions approaches, and human thermoregulation models.

Chapter 3

Thermal Comfort and Comfort Modelling

3.1 Introduction

This chapter reviews published findings on thermal comfort, ageing and the main predictions approaches adopted in evaluating thermal comfort. It also reviews major thermoregulation models in existence and introduced the human thermoregulation model selected for adaptation. The chapter further presents results of extended validation carried out on the selected model and concludes by outlining how literature informed the aim of the research.

3.2 Thermal Comfort

ANSI/ASHRAE (2010) defines thermal comfort as,

"*That condition of mind that expresses satisfaction with the thermal environments"*.

Admittedly there are large variations from person to person both physiologically and psychologically making it difficult to satisfy everyone in a given thermal environment (ANSI/ASHRAE, 2010). However the main aim of studying thermal comfort conditions is to be able to determine and provide conditions in the built environment which makes it possible for the achievement of that state of mind where occupants express satisfaction with their environment. To achieve this, many investigations were carried out to critically study and collect data on the responses of the body to various environmental conditions (Orosa, 2009). Extensive laboratory and field data has been collected which provided the necessary statistical data to define conditions that a specified percentage of occupants would find thermally comfortable (ANSI/ASHRAE, 2010).

Thermal comfort is dependent on six factors and these are; metabolic rate (heat generated in the body by oxidation and by external activities), clothing insulation (amount of clothes worn), air temperature (temperature around the body), air speed (rate of air movement across the body), relative humidity (defined as the amount of moisture in the air compared to the total amount of moisture that air can hold at a given temperature) and radiant temperature (heat radiation from heat source in the environment).

Of these, metabolic rate and clothing insulation are classified as personal and the other four are classified as environmental factors. As human beings increase their activity level the metabolic heat increases, Appendix A shows the metabolic rate values of various activity levels (Grimpampi, 2009).

3.3 Ageing and Comfort

In order to maintain a healthy and comfortable body temperature, the human body relies on the integration of virtually all systems to achieve this (Blatteis, 2012). Indeed the effect of ageing on the body has been widely established; however questions arise as to what implications this may have for the thermal comfort of the older person. Many research works have revealed that, when clothing, metabolic rate, body characteristics and ambient temperature are taken into consideration, older persons do not perceive comfort differently from younger people (Havenith, 2001a, van Hoof and Hensen, 2006). However analysis of the level of activity of older person revealed that as they age, their activity levels reduce which implies a lower metabolic heat production therefore leading to the need for a higher temperature for comfort as compared to younger person (Havenith, 2001a). Falk et al. (1994) investigated the response to rest and exercise in cold looking at effects of age and aerobic fitness of older subjects aged 63.5 years and 26.5 years for the younger group. The study concluded that during rest and low intensity exercise in cold, older men had a faster drop in core body temperature than younger men.

Potkanowicz et al.(2003) conducted an experiment looking at age effects on thermal, metabolic, and perceptual responses to acute cold exposure involving older subjects (67.7 years) and young subjects (26.7 years) who were exposed to ambient temperatures of 12°C, 18°C and 27°C. The study found that, there was an observed high mean skin temperature which suggests a deficit in the peripheral response leading to an increased heat loss over a protracted period of time (Potkanowicz et al., 2003). In exposure to heat, it has been found that, the rate of increase in the cardiac output of older subjects was significantly smaller when compared to that of younger persons (Blatteis, 2012). These studies highlight the challenges older persons face in maintaining the required core body temperature which may likely affect their comfort.

3.4 Thermal Comfort Approaches

Over the years, researchers have carried out many investigations and observations to better understand human thermal comfort and define standards which can be used in the design of comfortable environments for human habitation. Indeed, the human body is composed of many different complex systems and organs as such no two persons are the same. Even in an exposure to the same room climate it has been found that, the possibility of satisfying everybody rarely exists (Fanger, 1973). This may be as a result of the combination of different number of factors that affect human perception including physical, physiological and psychological (Fanger, 1973).

Despite these complexities, researchers have over the years made great strides to further understand how human beings perceive thermal comfort and how they react to various environmental conditions. In so doing, two main approaches have been developed with their own potentials and uncertainties. These approaches are the heat balance approach and adaptive approach. The heat balance approach also referred to as the rational approach relies on data sourced from climatic chamber experiments whilst the adaptive approach relies on data sourced from field experiments.

3.4.1 The Adaptive approach

This approach is based on the findings of thermal comfort surveys conducted in the field and is based on the basic principle that;

> *"if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort"* (Nicol, 2002).

The adaptive approach to thermal comfort analysis looks at the acceptability of the thermal environment in relation to the expectations of the occupants, their behaviour and comfort. Nicol (2002) states that:

"People have a natural tendency to adapt to changing conditions in their environment and this is expressed in the adaptive approach to thermal comfort".

In the adaptive approach, field studies are conducted with subjects going about their everyday lives where the investigator collects data about the thermal environment the subjects are exposed to and the simultaneous thermal response. This is usually done by asking them to assess their thermal sensation by means of comfort votes on a descriptive scale such as ASHRAE or Bedford scale (Table 3.1). By linking the comfort vote to people's actions, the adaptive principle links the comfort temperature to the context in which subjects find themselves (Nicol, 2002).

Table 3.1 Descriptors for ASHRAE and Bedford scales

ASHRAE descriptor	Numerical equivalent	Bedford descriptor
Hot	3	Much too hot
Warm	2	Too hot
Slightly warm	1	Comfortably warm
Neutral	0	Comfortable
Slightly cool	-1	Comfortably cool
Cool	-2	Too cool
Cold	-3	Much too cool

3.4.2 The heat balance approach

The heat balance approach seeks to explain the response of people to their thermal environment in terms of the physics and physiology of heat transfer Nicol (2002). One of the famous works in this field which has become the bases for current standards ISO 7730 and ASHRAE 55 was the investigations carried out by Fanger in 1970 where he exposed 1,296 young Danish students dressed in standardized clothing and undertaking standardized activities to different thermal environments (Fanger, 1970). ASHRAE's thermal sensation scale was used to determine the thermal state of the participants. Fanger combined the theories of heat balance with physiology of thermoregulation to determine a range of comfort temperature which are appropriate for occupants. Fanger (1967) developed the comfort equation (Fanger, 1967) which was later expanded in (Fanger, 1970). The expanded equation related thermal conditions to the seven point ASHRAE thermal sensation scale and became known as the Predicted Mean Vote (PMV). Fanger defines Predicted Mean Vote (PMV) as the mean thermal sensation vote for a large group of persons for any given combinations of the thermal variables (air temperature, mean radiant temperature, air velocity and relative humidity) including the activity and clothing levels.

The PMV model is in most cases referred to a static model in that where step changes in thermal conditions are involved, it cannot predict the exact response (van Hoof et al., 2010). The PMV was later incorporated into the PPD (Predicted Percentage of Dissatisfied) which describes the percentage of occupants in a thermal environment who are dissatisfied with the conditions as shown in Figure 3.1. Practically, it is impossible to provide thermal satisfaction for everyone in a given environment as such 5% PPD is the accepted lowest (Fanger, 1970).

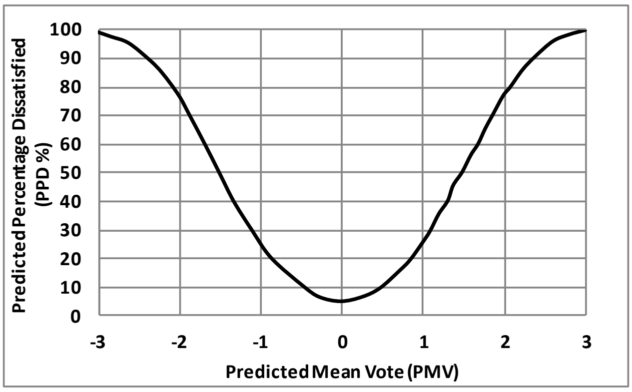

Figure 3.1 Predicted Percentage of Dissatisfied (PPD) as a function of Predicted Mean Vote (PMV)

Fanger's PMV-PPD model has found wide acceptability and applicability in design and assessment of thermal comfort. Besides Fanger's model, many other thermal models based on climatic chamber experiments have been proposed over the years, ranging from simple cylinder models to complex multi-segment ones.

3.5 Human thermoregulation Models

Human thermoregulation models have over the years evolved from a single-node form where the human body is represented with single homogenous materials to more complex multi-layered and multi-element models (Schappeler, 2011). With the advent of computers and increase in their computing capabilities, current model of human thermoregulation are able to break the body down into several layers and segments which facilitates better understanding of the human body. The evolutionary stages can be classified into four categories (Fu, 1995) comprising;

- One-node thermal models
- Two-node thermal models
- Multi-node thermal models
- Multi-element thermal models

One-node thermal models use only one node (single homogenous material) and does not include a thermoregulatory system to represent the human body whiles in two-node models, the body is divided into two concentric shells of central core which represents the internal organs and other shell being the skin layer (Holopainen, 2012). Multi-node thermal models are extensions of the two node thermal models but they include more than two concentric shells. In the case of multi-element thermal models they divide the body into several elements with each representing a separate portion or locations of the body (Schappeler, 2011) . Energy balance equations are then established for each body part along with thermoregulatory control equations for blood flow rate, shivering, constriction, dilation and sweating (Holopainen, 2012).

Stolwijk (1971) developed a more detailed human thermoregulation model which forms the basis of most of the models in existence today. The model set out the fundamental concept, algorithm, physical constants and physiological control sub-systems for many multi-nodes models (Alfano, 2008**).** Stolwijk's (1971) dynamic multimode human thermoregulation model divides the body into six segments, comprising the head, trunk, arms, legs, and feet. Each of these segments is divided into four layers of core, muscle, fat, and skin (Stolwijk, 1971). In all a total of 25 nodes were used to represent the thermal characteristics of the body. The 25th node represents the central blood pool which is thermally connected to all other nodes. Some of the major models which have found wide applicability in both industry and academia include: (Huizenga et al., 2001, Gagge et al., 1971, Wissler, 1964, Stolwijk, 1971, Gardner and Martin, 1994, Tanabe S., 2002, Fiala, 1998, Ying et al., 2009).

Gagge et al.(1971) developed a two-node model of the human body temperature regulation in which skin temperature and core temperature serve as the main controllers. The model incorporates the effector processes of vasoconstriction, vasodilation and sweat secretion (Gagge et al., 1971). The model was divided into two main parts that is the passive system and the active system. The passive system is governed by the heat balance equations developed for humans. Overall there are seven independent environmental variables in the model which includes, metabolic rate, work done, the combined heat transfer coefficient for radiation and convection, the conductive heat transfer coefficient, clothing insulation, ambient temperature, humidity, and air movement. The principal physiological factors predicted by the model include skin temperature, core temperature, total evaporative heat loss and skin blood flow. Gagge et al.(1986) improved on the original model, incorporating other control functions including blood flow rate, shivering metabolic rate and sweat rate in the active system.

Wissler (1964) developed a mathematical model to simulate the physical characteristics of the human thermal system in the transient state. In the model the body was divided into 15 geometrical regions comprising the head thorax, abdomen, the arms and legs subdivided. In each of the segments of the model, the large arteries and veins were approximated by an arterial pool and venous pool which was distributed radially throughout the segment (Wissler, 1964). Heat accumulation in the blood of the large arteries and veins and the heat transfer from them to the surrounding tissues were also modelled. Each of the 15 geometrical segments were further subdivided into 15 radial sections which provided a greater freedom in the assignment of physical properties such as thermal conductivity and rate of blood flow to the capillaries (Wissler, 1964). The model also took into consideration, transient factors using a transient bioheat equation (Holopainen, 2012).

Gardner and Martin (1994) developed a model of the human thermoregulatory system for normal subjects and burned patients. In this model the human body was split into eleven segments each having a core, muscle, fat and skin layers. Heat transport though blood flow and conduction are simulated and surface heat loss is separated into radiative, convective and evaporative components (Gardner and Martin, 1994). Measurement of skin temperature and evaporation of moisture were made from the body of 22 normal subjects over a range of environmental temperature from 20°C to 40°C. The model was adapted to describe the responses of burn patients by the introduction of skin layer destruction, increased body metabolism and fluid loss from wounds (Gardner and Martin, 1994). The model showed that the ambient temperature at which sweating occurs increases with the area of burn injury and this was confirmed by clinical observations (Gardner and Martin, 1994). The model has been used to predict optimum environmental temperatures for the treatment of patients with burn wounds of varying extent.

Tanabe et al. (2002) presented a thermoregulation model based on the Stolwijk model. The model consisted of 16 body segments corresponding to the thermal manikin with each segment made up of four layers of core, muscle fat ad skin. The body segments include the head, chest, back, pelvis, left shoulder, right shoulder, left arm, right arm, left hand, right hand, left thigh, right thigh, left leg, right leg, left foot, and right foot. The 65th node represents the central blood compartment which exchanges convective heat with other nodes via the blood flow (Tanabe et al., 2002). The convective and radiant heat transfer coefficients and clothing insulation were all derived from the thermal manikin experiments (Tanabe et al., 2002).. The model represents that anthropometric data of an average man with a body weight of 74.430kg and body surface area of 1.87 m^2. Tanabe et al. (2002) proposed a thermoregulation model combined with radiation exchange model and computational fluid dynamic (CFD).

Huizenga et al.(2001) developed a thermoregulation model which was based on the Stolwijk model and Tanabe model but the model contains a number of significant improvements over the Stolwijk model. This Huizenga model also known as the Berkeley multi-node comfort model uses 16 body segments (compared to 6 by Stolwijk) and this corresponds to the UC Berkeley segmented thermal manikin. Each segment is modelled as four body layers (core, muscle, fat, skin tissues) and a clothing layer. Physiological mechanisms such as vasodilatation, vasoconstriction, and sweating and metabolic heat production are explicitly considered (Huizenga et al., 2001, Huizenga et al., 1999). According to Huizenga et al.(2001) the use of 16 body segments in the model provides two important advantages, first it improves the models ability to predict the effects of asymmetric environments and second, the models segmentation corresponds directly to the UC Berkeley segmented thermal manikin which has the ability to accurately measure heat transfer coefficients and clothing simulation values for individual body parts (Huizenga et al., 2001). The model was developed based on experiments carried out on 109 human subjects' tests which were performed under non-uniform and transient conditions in the UC Berkeley controlled environmental chamber. In these tests, local body surfaces of subjects were independently heated or cooled while the rest of the body was exposed to a warm, neutral or cool environment (Huizenga et al., 2001). The model is capable of prediction human physiologic response to transient, non-uniform thermal environments and incorporates a local discomfort model and has a friendly user interface as well as a body builder which allows users to adjust many internal parameters (Huizenga et al., 1999).

Fiala Model was developed in the 1990s and inherited the majority of concepts of the earlier models proposed by Stolwijk (1971). In the model the heat transfer process in the human body and the thermoregulatory responses were modelled to maintain a balance between heat gains and loss (Fiala, 1998). The model was designed to represent an "average man" and profiles the human body as two interacting systems; of active system and passive system. It incorporates a physiological based thermal comfort model which has the ability to predict the thermal behaviour of a person in a given environment in terms of sweating, shivering, skin temperature, blood perfusion rate, and other physiological parameters in steady state and transient environments (Fiala, 1998). It also predicts the Dynamic Thermal Sensation (DTS), and the associated Predicted Percentage of Dissatisfied (PPD) (Fiala, 1998). The model extends the predictability of human thermal sensation from moderate to thermally stressful situations, from steady states to transient conditions, and from lower activity levels to high levels up to 10 met (Fiala, 1998, Fiala et al., 2001). Table 3.2 show a list of some other existing thermoregulation models.

Table 3.2 Other existing thermoregulation models

No.	Model / Year	Type of Model	Particulars
1	**Bruse (2005)**	Simple dynamic 2-node model	A model of the human thermoregulatory system and its application in a multi-agent simulation system
2	**Salloum et al.(2007)**	A Multi-node model	A mathematical multi-segmented model based on an improved Stolwijk model developed for predicting nude human thermal and regulatory responses with body segments and the environment
3	**Holopainen and Tuomaala (2010)**	A Multi-node model	Human thermal model integrated in a building simulation environment for a more accurate estimation of thermal comfort in transient conditions
4	**Severens et al.(2007)**	A Multi-node model	A model to predict patient temperature during cardiac surgery
5	**Al-Othmani et al.(2008)**	A Multi-node model	A multi-segmented human bioheat model for transient and asymmetric radiative environments (Improvement on (Salloum et al., 2007)
6	**Havenith (2001)**	Individualized model of human thermoregulation	Expansion of a population-based dynamic model of human thermoregulation incorporating individualized characteristics.
7	**Streblow et al. (2008)**	Coupled human thermal model with CFD	Coupled a multi-node thermal regulatory model with CFD to predict thermal sensation and comfort
8	**Ying et al.(2009)**	A multi-node infants model	An improved mathematical model of thermal physical response of naked infants

3.6 Model Review Summary

Human thermoregulation models in existence provide a unique opportunity for exploring and understanding the intricate thermal behaviours of the human body. From the reviews conducted in this research one unique similarity of the models was the data used in their formulation. Most of their developers used data sets from test subjects who were mostly young people thus the description of the models as average person's models. This therefore raises questions as to their suitability for use in the thermal analysis of older persons.

However, as the world is rapidly being confronted with the increase in ageing populations, the need for a customized thermoregulation model for the older population cannot be overstated. Indeed there is evidence that the current models may not predict thermal comfort for the elderly satisfactorily (van Hoof and Hensen, 2006).

3.7 Choice of model for modification

Apart from being developed in the Institute of Energy and Sustainable Development (IESD) with the institute having access to the original codes of the programme, the Fiala model has found wide applicability in various fields of study. These include biometeorology, clothing research, clinical, car and safety applications (Fiala et al., 2010). Many claim this is as a result of its flexibility, robustness and detailed representation of the human body systems as compared to the other models of thermoregulation.

In the built environment, the model was used in predicting the physiological and comfort responses of the stadium spectators during the design of Sydney Olympic Stadium (Australia) for the 2000 Olympic Games (Fiala and Lomas, 1999). Generally the model enables the thermal effects of a building's design on human beings to be quantified and evaluated were complex boundary conditions, thermal situations approaching health and safety limits, and the effect of exposure times can be analysed (Fiala, 1998). In the commercial setting the model has found applicability in commercial packages including THESEUS-FE (P+Z-Engineering, 2009) a professional software tool for steady-state and fully transient thermal management applications including cabin interior analysis and passenger comfort. This software package also has wide ranging applicability in the automotive, transportation and aerospace industry. Another commercial package is the RadTherm (Human thermal Comfort) (ThermoAnalytics, 2012) whose application includes architectural analysis, passenger compartment design for vehicles, trains, and aircrafts, fire fighter safety equipment and advanced materials for clothing systems. It can also be used to examine the thermal safety of aircraft pilots and passengers under extreme environments. In the medical field the model was adapted for use in the design of a computer model that can be used to predict the temperature responses of patients who undergo cardiac surgery (Severens et al., 2007).

Another area where Fiala model has found wide applicability was when it was used in the design of the Universal Thermal Climate Index (UTCI) under the European project COST 730 project. The Universal Thermal Climate index is aimed at the assessment of outdoor thermal conditions in the major felids of biometeorology based on the physiological response of the human body. Fiala model was selected for its advancement and precision (Psikuta, 2009a, Peter Bröde, 2010)**.** Different validation studies involving "*climate-chamber physiological and thermal comfort experiments, exposures to uncontrolled outdoor weather conditions, extreme climatic and radiation asymmetric scenarios show that the model does predict physiological and perceptual responses typically within the standard deviation of the experimental observations"* (Fiala et al., 2010).

The Fiala model is a population-based model designed to represent an "average man" and models the human body as two interacting systems comprising of the active system and the pasive system structure (section 3.5). The following section (3.8) summarises the major equations of the Fiala model (Fiala, 1998, Fiala et al., 2010).

3.8 The Passive System

The passive system of the Fiala model represents the body structure of the human body with detailed information on its anatomic and geometrical properties. It consist of 15 spherical/cylindrical body elements including head, neck, face, shoulders, arms, hands, legs, feet, thorax and abdomen. Seven different tissue materials are used to define the body which includes; brain, muscle, lung, bone, fat, viscera and skin. Each body element consists of annular concentric tissue layers which are subdivided into one or more nodes with each node being assigned appropriate thermo physical and thermo physiological properties (Fiala, 1998, Fiala et al., 2001, Fiala et al., 2010). The model is a representation of an average man with the following body parameters;

- Body weight of 73.5 kg,
- Body fat content of 14%,
- Dubois-area of 1.86 m^2,
- Basal metabolism of 87 W,
- Basal cardiac output of 4.9 L min-1.

These values are appropriate for a reclining adult in a thermo-neutral environment of 30°C where no thermoregulation occurs. Appendix B shows the body structure segmentation of the Fiala Model (Fiala, 1998).

3.8.1 Heat transport within the body

The model uses the Pennes' (1948) bioheat equation of heat transfer occurring in the living tissue as shown in equation (3.1). It predicts the dynamic heat transport within the body taking into account the blood perfusion, metabolic heat production, heat conduction from warmer to colder tissue locations and heat storage.

$$k\left(\frac{\partial^2 T}{\partial r^2} + \frac{\omega}{r}\frac{\partial T}{\partial r}\right) \quad + \quad q_m \quad + \quad \rho_{bl} w_{bl} c_{bl}\left(T_{bl,a} - T\right) \quad = \rho c \frac{\partial T}{\partial t}$$

Conduction **Metabolism** **Blood heating** **Heat storage** (3.1)

Where:

- T = tissue temperature;
- r = radius;
- ω = geometry factor:
- q_m = metabolism;
- ρ_{bl} = density of blood;
- w_{bl} = blood perfusion rate;
- C_{bl} = heat capacitance of blood;
- T_{bla} = arterial blood temperature;
- t = time;
- ρ = tissue density;
- c = tissue heat capacitance;
- k = tissue conductance;

This equation is applied to all tissue nodes using the appropriate material constants k, ρ, c, the basal heat generation term q_m, and basal blood perfusion rate w_{bl} for each tissue layer (Fiala, 1998).

3.8.2 Metabolic heat production

The metabolic heat production in the model is calculated as:

$$q_m = q_{m,bas,0} + \Delta q_m \qquad (3.2)$$

Where $q_{m,bas,0}$ is the basal value and in the muscles, additional heat Δq_m may be produced by local autonomic thermoregulation, while exercising and/or shivering. This additional heat may contain three components including, changes in the basal metabolism, ($\Delta q_{m,bas}$) and additional metabolism by shivering and working, $q_{m,sh}$ and $q_{m,w}$, respectively (Fiala, 1998) (equation 3.3).

$$\Delta q_m = \Delta q_{m,bas} + q_{m,sh} + q_{m,w} \tag{3.3}$$

The change in the basal metabolism $\Delta q_{m,bas}$ is the difference between the actual basal rate and the basal rate corresponding to neutral thermal conditions (equations 3.4).

$$\Delta\, q_{m,bas} = q_{m,bas,0} * \left[2^{\frac{T-T_0}{10}} - 1\right] \tag{3.4}$$

The shivering term $q_{m,sh}$ in equation 3.3 is a portion of the overall regulatory response elicited by the active system and the working term ($q_{m,w}$) is defined as:

$$q_{m,w} = \frac{\partial(a_{m,w}H)}{\partial V_{msc}} \tag{3.5}$$

Where $a_{m,w}$ is a coefficient distributing the overall metabolism due to exercise over body elements, V_{msc} is the corresponding body element muscle volume, and H is the internal whole body workload (Fiala, 1998), this is defined as:

$$H = act\frac{M_{bas,0}}{act_{bas}}(1-\eta) - M_{bas,0} \tag{3.6}$$

Where act_{bas} is the activity level at the basal state of the body given as (act_{bas} = 0.8 met). From the above equation the term (1- η) is that fraction of the overall metabolic heat produced which remains for warming the body, the one which is not converted into external mechanical power (Fiala, 1998). Human mechanical efficiency (η) is not constant but rises with increasing activity levels (Fiala, 1998). Human mechanical efficiency (η) is calculated using equation 3.7.

$$\eta = 0.2 * \tanh\{b_1 * act + b_0\} \tag{3.7}$$

3. 8.3 Heat exchange with the environment

The body surface plays a major role in heat loss from the body to the environment in terms of radiation, convection, skin evaporation, contact heat flux and also by respiration. Figure 3.2 shows the boundary condition of a leg sector in a hot environment.

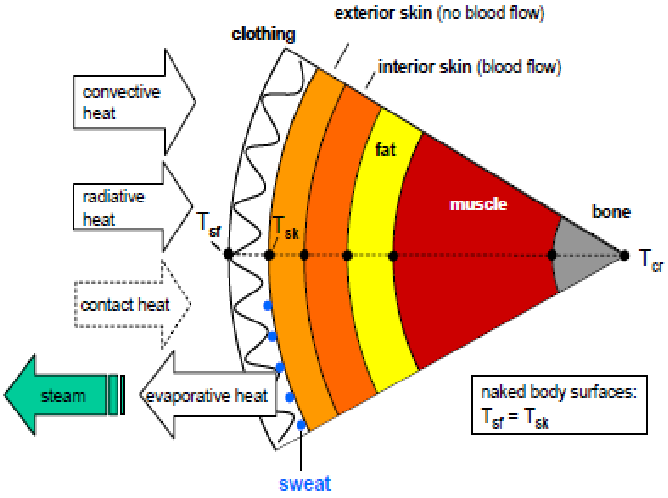

Figure 3.2 Boundary conditions of a leg sector (P+Z-Engineering, 2009)

The heat loss $\boldsymbol{q_{sk}}$ [W/m^2] at the body surface is a sum of heat exchange by;

- Convection ($\boldsymbol{q_c}$),
- Radiation ($\boldsymbol{q_r}$),
- Irradiation from high-temperature sources (e.g. the sun) ($\boldsymbol{q_{sR}}$),
- Evaporation of moisture from the skin ($\boldsymbol{q_e}$),
- Respiration via convection ($\boldsymbol{C_{rsp}}$)
- Evaporation ($\boldsymbol{E_{rsp}}$).

The total heat flux (q_{sk}) is equivalent to the sum of individual heat exchanges calculated as:

$$q_{sk} = q_c + q_r - q_{sR} + q_e + (C_{rsp} + E_{rsp}) \tag{3.8}$$

3.8.4 Convective heat flux

The convective heat exchange *qc* between the skin sector of surface temperature T_{sf} and an ambient air temperature Ta is modelled taking into consideration both natural (free) and forced convection using a combined convection coefficient $\boldsymbol{h_{c,\ mix}}$ (Fiala, 1998) this is given in equation 3.9.

$$q_c = h_{c,mix} * \left(T_{sf} - T_a\right) \tag{3.9}$$

Where $h_{c,mix}$ is given as:

$$h_{c,mix} = \sqrt{\alpha_{nat}\sqrt{T_{sf} - T_a + \alpha_{frc}}v_{a,eff} + \alpha_{mix}} \tag{3.10}$$

This convection coefficient ($\boldsymbol{h_{c,\ mix}}$) depends on the location on the body, the temperature difference between the surface and air and the effect air speed *($v_{air,\ eff}$ (m/sec)).*

3.8.5 Radiant heat flux

The radiant heat flux (q_r) used in the model is defined as:

$$q_r = h_r * \left(T_{sf} - T_{sr,m}\right) \tag{3.11}$$

Where h_r is the local radiative heat exchange coefficient and $T_{sr,m}$ is the mean temperature of the surrounding surfaces. The local radiative heat exchange coefficient h_r is calculated as:

$$h_r = \sigma \mathcal{E}_{sf} \mathcal{E}_{sr} \psi_{sf-sr} \left(T_{sf}^{*2} + T_{sr,m}^{*2}\right)\left(T_{sf}^{*} + T_{sr,m}^{*}\right) \tag{3.12}$$

- Where: (σ) is the Stefan-Bolzmann constant given as ($\sigma = 5.67 \cdot 10^{-8}$ W m^{-2}K^{-4}),
- ε_{sf} and ε_{sr} are the emission coefficients of the body surface sector considered and of the surrounding.
- $\Psi_{sf\text{-}sr}$ is the corresponding view factor

- T_{sf}^{*} and $T_{sr,\ m}^{*}$ are the absolute temperatures of the body surface sector and of the surrounding surfaces 'seen' by the body sector

3.8.6 Irradiation

Irradiation is defined in the model as:

$$q_{sR} = \alpha_{sf} * \psi_{sf-sr} * S \tag{3.13}$$

Where:

- α_{sf} is the surface absorption coefficient and depends on the colour of the covering material,
- S is the radiant intensity
- $\Psi_{sf\text{-}sr}$ is the view factor between the sector and the surrounding envelope

3.8.7 Clothing

There exist databases on clothing in the model, which is used to compose various clothing profiles and are implemented in the simulations (Fiala, 1998). The local sensible effective heat transfer coefficient of clothing insulation U_{cl}^{*} [W m^{-2}K^{-1}] is calculated as:

$$U_{cl}^{*} = \frac{1}{\sum_{i=1}^{m}(I_{cl}^{*})_i + \frac{1}{f_{cl}^{*}\left(h_{c,mix} + h_r\right)}} \tag{3.14}$$

Where:

- $I_{cl\ ,i}^{*}$ [W m^{-2}K^{-1}] is the 'local' heat resistance of i-th clothing layer
- f_{cl}^{*} the 'local' clothing area factor of the outer clothing-layer,
- $h_{c,mix}$ and h_r are the actual local coefficients for convection and radiation,

3.8.8 Respiratory Heat loss

The heat loss from respiration can be divided into two parts that is the convective (Crsp) and evaporative (Ersp) components given as

$$E_{rsp} = 4.373 \int q_m \, dV(0.028 - 6.5 * 10^5 T_a - 4.91 * 10^6 P_a) \tag{3.15}$$

$$C_{rsp} = 1.948 * 10^3 \int q_m \, dV(32.6 - 0.066 T_a - 1.96 * 10^{46} P_a) \tag{3.16}$$

The total respiratory heat loss (Q_{rsp}) is calculated from equation 3.17

$$Q_{rsp} = E_{rsp} + C_{rsp} \tag{3.17}$$

3.9 The Active System

The active system of the Fiala model (Figure 3.3) simulates responses of the human thermoregulatory system, which comprises, sweating, vasodilation, vasoconstriction and shivering. The model uses temperature readings of the skin (T_{skm}) and the head core (hypothalamus, T_{hy}) and the rate of change of skin temperature (dT_{sk} /dt) as input signals into the regulatory centre (central nervous system). The local autonomic regulation utilizes local skin and tissue temperatures to modify local sweat rates, blood flows, and tissue metabolic rates (Fiala, 1998).The mean skin temperature **(***Tsk,m*) is computed by the model using equation 3.18.

$$T_{skm} = \sum_{i}^{elem.} \left(\alpha_{sk.i} \sum_{j}^{sect} \frac{A_{sk,i\,j}}{A_{sk,i}} T_{sk,i\,j} \right) \tag{3.18}$$

Where:

- $a_{sk,i}$ is the coefficient for skin sensitivity the body element under consideration
- $A_{sk,i}$ [m^2] and $A_{sk,ij}$ [m^2] are the skin surface areas
- $T_{sk,ij}$ is the corresponding local skin temperature.

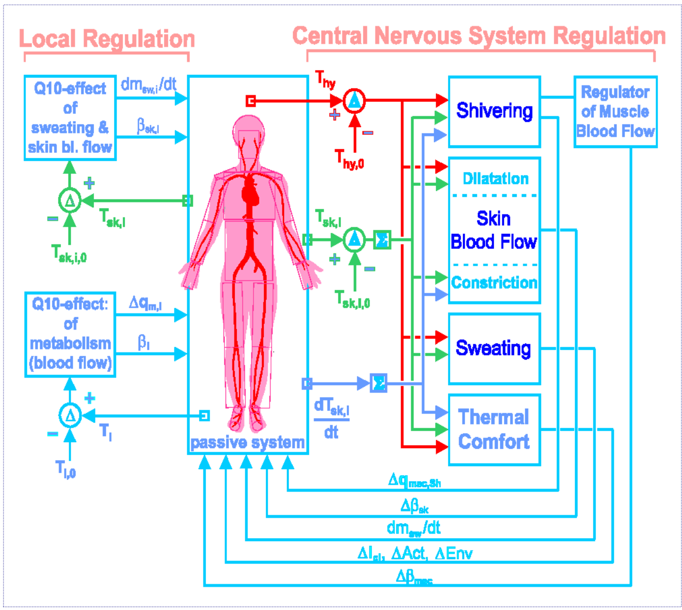

Figure 3.3 Block diagram of the active system, Fiala et al. (2001).

The control equations (below) were developed by means of regression analysis using measured responses from several experiments from different exposures.

Sweating:

$$SW = [0.8\, tanh(0.59\Delta T_{skm} - 0.19) + 1.2]\Delta T_{skm} + \left[5.7\, tanh\left(1.98\Delta T_{hy} - 1.03\right) + 6.3\right]\Delta T_{hy} \quad (3.19)$$

Vasodilatation:

$$DL = 21[tanh(0.79\Delta T_{skm} - 0.70) + 1]\Delta T_{skm} + 32\left[tanh\left(3.29\Delta T_{hy} - 1.46\right) + 1\right]\Delta T_{hy} \quad (3.20)$$

Shivering:

$$SH = 10[tanh(0.48\Delta T_{skm} + 3.62) - 1]\Delta T_{skm} - 27.9\Delta T_{hy} - 28.6 + 1.7\, \Delta T_{skm}\left(\frac{dT_{skm}}{dt}\right) \quad (3.21)$$

Vasoconstriction:

$$CS = 35[tanh(0.34\Delta T_{skm} + 1.07) - 1]\Delta T_{skm} - 7.7\Delta T_{hy} - 3.9\, \Delta T_{skm}\left(\frac{dT_{skm}}{dt}\right) \quad (3.22)$$

3.10 Applying the Fiala model

The Fiala model simulates the physiological state of the body using a configured file. This configured file contains various defined sets of parameters which include the ambient temperature, the radiant temperature, air velocity, relative humidity and the activity level. The aforementioned parameters are accessed by the configuration file from the boundary condition files. Other parameters in the configuration file include the clothing level of the person and the time of change of clothing. The model has an option to set the initial conditions of the subjects prior to the experiment. The output from the model is reported in the output file which contains the simulated physiological responses of the average person. These include the mean skin temperature, the hypothalamus temperature, and rectal temperature, sweating rate and shivering intensity of the person, skin blood flow and the dynamic thermal sensation. Other output parameters include the local skin temperature of the body, local blood flow, and core temperatures of the various segments of the body.

The Fiala Model has shown good agreement with experimental data of average persons in most case (young subjects) but as to whether its prediction reflects the responses of the older persons is unknown. The exercise was carried out to analyse how the Fiala models results compares to the experimental results of the young person and the older person. In this exercise, Fiala model was used to simulate various independent investigations where young and older subject were exposed to various degrees of thermal stress. Table 3.3 shows the list of experiments used.

Table 3.3 Extended validation experiments

Test Case	**Author and Year**	**Title of Study**	**Type of Exposure**
1	**Inoue et al.(1992)**	Thermoregulatory responses of young and older men to cold exposure	Ambient temperature **(Ta = 12°C)**
2	**Inoue et al.(1992)**	Thermoregulatory responses of young and older men to cold exposure	Ambient temperature **(Ta = 17°C)**
3	**Kenney and Armstrong,(1996)**	Reflex peripheral vasoconstriction is diminished in older men	Ambient temperature **(Ta = 28 to 10°C)**
4	**Krag (1952)**	Stability of Body Function in the Aged II Effect of exposure of the body to heat	Ambient temperature **(Ta = 42°C)**

In Test Case 1, the experiment involved nine (9) young men and ten (10) old men. The Older group of subjects ranged in age from 60 to 71 years and the younger group from 20 to 25 years. During the experiment, subjects wearing only swimming trunks sat on a chair in a comfortable environment with ambient temperature (Ta = 28 °C) for at least 60 minutes (referred to as equilibrium period). During this time, the measurement apparatus were attached to the subjects. After this period the subjects stood and entered the environmental chamber and sat quietly for 60 minutes at ambient temperature of (Ta =12°C) and relative humidity (RH) of 45%. Figure 3.4 shows the mean skin temperature experimental results and prediction of the Fiala model whilst Figure 3.5 shows the results of the rectal temperature.

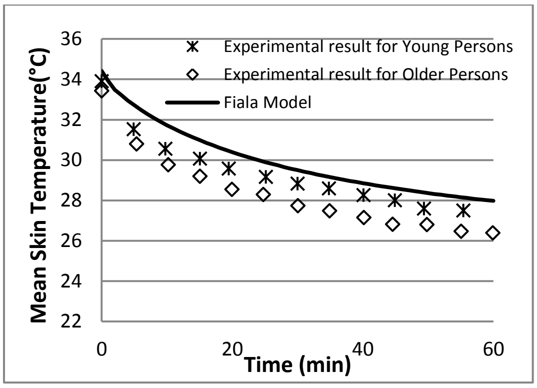

Figure 3.4 Mean Skin Temp of 12°C exposure

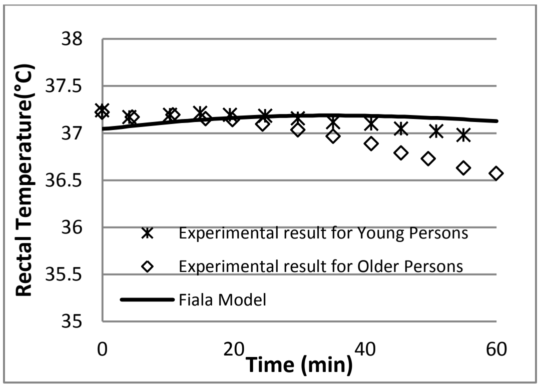

Figure 3.5 Rectal Temp of 12°C exposure

It can be seen from Figure 3.4 and 3.5 that, the Fiala Models results follow the trend and show good agreement with young person's experimental data. In Figure 3.4, at the end of the experiment the results for the mean skin temperature and core temperature (Figure 3.5) were generally in good agreement with experimental data for young subjects. The mean skin temperature predictions show slight deviation from the experimental value between times 5 minutes to 15 minutes (Figure 3.4), but from 15 minutes until the end of the experiment, the results of the model show relatively good agreement with experimental data. However the core body temperature (rectal temperature) recorded minimal variation in predicted value as compared to the experimental result (0.25°C) at the start of measurement but by 25 minutes in to the experiment, the prediction of the model show good agreement with experimental data (Figure 3.5)

Test Case 2 followed a similar test protocol of test case 1 where ten (10) Old men with age range of 60 to 71 years and nine (9) young men with age range of 20 to 25 years wearing only swimming trunks sat on a chair in a comfortable environment with ambient temperature (Ta = 28°C) for at least 60 minutes. After this period the subjects stood and entered the environmental chamber and sat quietly for 60 minutes at ambient temperature of (Ta =17°C) and relative humidity (RH) of 45%. Figure 3.6 and 3.7 show the mean skin temperature and rectal temperature results of the test.

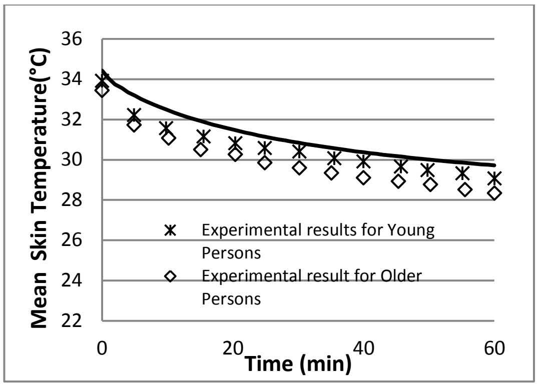

Figure 3.6 Mean Skin Temp of 17°C exposure

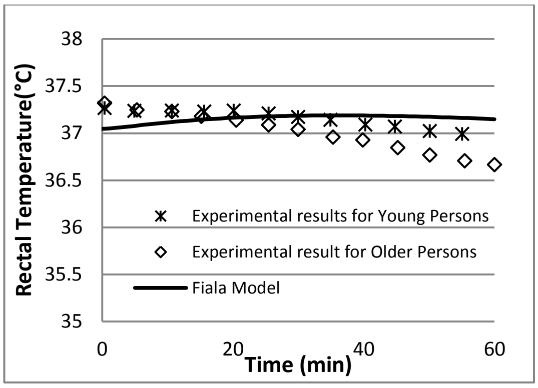

Figure 3.7 Rectal Temp of 17°C exposure

In Figure 3.6 and 3.7, the Fiala Models results follow the same trend as the experimental data for young persons. In Figure 3.6, at the end of the experiment the predictions for the mean skin temperature and core temperature (Figure 3.7) were in good agreement with experimental data. The mean skin temperature predictions show good agreement with experimental data but for the core temperature (rectal temperature) there was a small variation in predicted value as compared to the experimental value of (0.25°C) at the start of measurement but by 20mins into the experiment, the prediction of the model show relatively good agreement with experimental data.

In Test Case 3 the experiment involved six (6) young men and six (6) older men with age range of 58 to 67 years for older men and 22 to 31 years for the young men. It was reported that on arrival at the testing site, subjects drank 400ml of water, after which they were instrumented and a clothing insulation of 0.6 clo was worn. They then entered the environmental chamber where they sat comfortably in a semi-reclining posture for 120 minutes (2 hours). Subjects were instructed to remain as relaxed as possible without falling asleep. The ambient temperature was controlled to ensure repeatability between subjects. The temperature was held at 20°C for the first 30 minutes followed by a systematic lowering over the next 40 minutes in steps of 2°C every 5 minutes. The temperature was then held constant at 10°C for the final 50 minutes of the test. Figure 3.8 shows the results of the esophageal temperature and the prediction of Fiala model whiles Figure 3.9 shows the mean skin temperature

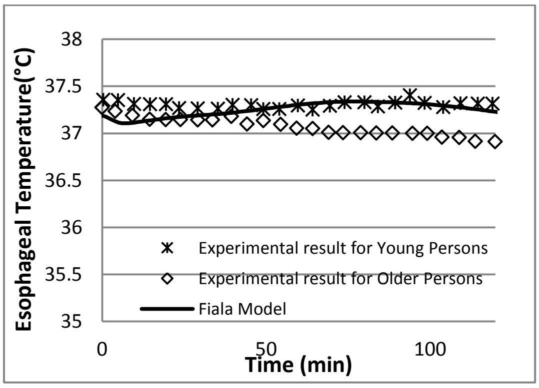

Figure 3.8 Esophageal Temp of 28-10°C exposure

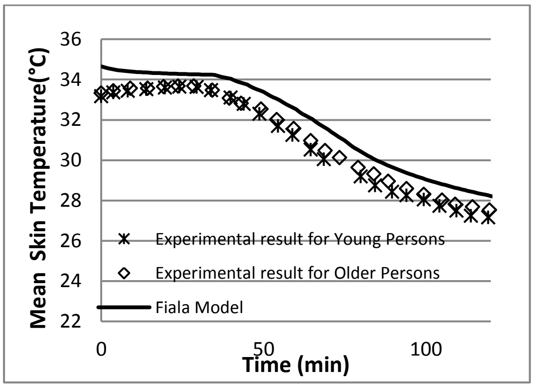

Figure 3.9 Mean Skin Temp of 28-10°C exposure

It can be seen from Figure 3.8 and 3.9 that the Fiala Models results follow the trend of young person's experimental results. In Figure 3.8, Fiala Models rectal temperature predictions show good agreement with experimental results. In the case of mean skin temperature, the models results show some variations over the durations of the test (Figure 3.9).

In Test Case 4 the investigation involved two groups of subjects, including 12 young adults and 14 elderly subjects. The age of the subjects ranged from 57 to 95 years for the older group and 21 to 32 years for the younger group. Subjects wearing shorts were observed under fasting basal condition where initial base line measurements were recorded. After this period subjects were then moved to the experimental cabinet with ambient temperature of the cabinet was set between the range of 38°C and 45°C (42°C selected for the simulation) with 100% relative humidity. No activity was reported for the subjects as such the selected activity was sitting (0.8met). Figure 3.10 shows the rectal temperature experimental results and prediction of the Fiala model.

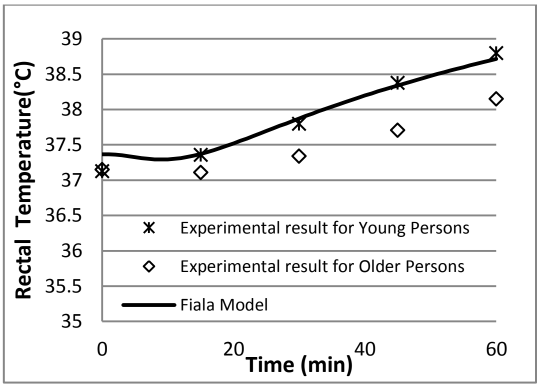

Figure 3.10 Rectal temperature 42°C

It can be seen from Figure 3.10 that Fiala Models result show good agreement with experimental data of young persons. The core temperature (rectal temperature) revealed that the predictions of the model were in good agreement with experimental data from the beginning of the experiment until the end.

3.10.1 Summary of Observations

In all the four (4) cases simulated, it can be concluded that, the Fiala Model displays a strong capability of predicting for the young subject. In test case 1, 2, and 4, the model's predictions show good agreement with experimental data. In test case 3, even though the models predictions were not in very good agreement with the experimental predictions of the mean skin temperature, the core temperature however show good agreement. Overall the models predictions follow the trend of all the experimental results. It can therefore be deduced from the experiments that, Fiala model in its current form and composition does predict well for the young person but as seen from the results it may not satisfactorily predict for the older population. This therefore makes a strong case for its adaptation to incorporate the thermo physical characteristics associated with the ageing human body in order for it to be used for thermal state analysis of the older people.

3.11 How the literature informed the research aim

From the reviews conducted, most of the models in existence derived their design data from test results from subjects who were mostly young persons. As shown in section 3.10 where an established model (Fiala Model) was applied to four test cases the predictions show good agreement with experimental results of the younger persons than the older person. As yet, there is no model which has been exclusively modified to predict for the older persons based on experimental data sets of the older person. Indeed there are several reasons to do this and literature reviewed as part of this research gives credence to this. In the field of human thermoregulation, many authors agree that there is still more room for improvement in the analysis and prediction of the active system of the human body (Severens, 2008). Many authors and researchers have also highlighted the changing of the earth's climatic conditions leading to increased variability in weather conditions which may prove problematic for the older person due to the varying effect of ageing on their body systems. The review identified the following gaps in knowledge that this research seeks to address, notably;

- The lack of a detailed thermoregulation model for the prediction of the thermal response of the older population.
- The lack of a robust methodology to be adopted for the modification of the existing models to incorporate detailed thermo physical and regulatory parameters of the older person.

These gaps have subsequently informed the aim of the research as to;

Develop a customized human thermoregulation model which can be used for predicting the thermal response of older persons.

It is intended that by achieving the aim a new tool will be available to the research community and built environment professionals which can assist in enhancing further understanding of the ageing effect on the human body and it thermal response patterns. A tool which illuminates the priorities especially designers and built environment specialists/managers should consider when designing/managing occupancies for the elderly by pre-testing various design scenarios and analysing their effect on the thermal state of the elderly person and possible energy use considering.

3.12 Chapter Summary

This chapter reviewed thermal comfort and the effect of ageing on thermal comfort in the older population. It also reviewed the main approaches (adaptive and rational) adopted in evaluating the thermal comfort of humans. Various human thermoregulation models were also reviewed with the discovery that most of the well-established and most used thermoregulation models in existence were designed based on average person thermo physical parameters. Typical characteristics of ageing in human body organs have not been incorporated in their design. A selected thermoregulation model (Fiala Model) was extensively reviewed and an extended validation carried out which revealed that in its current state and form it does predict well for the young person but may not satisfactorily predict for the older population. The chapter concludes by setting out how literature informed the main aim of research with focus on the gaps identified in knowledge. Chapter 4 proceeds with the design of the passive system (body structure).

Chapter 4

Design of Passive System-Typical Older Person

4.1 Introduction

This chapter reviews published findings on ageing of the human body and focuses on the selection of a representative typical average age for older persons which was used for extracting relevant data. It also reviews various research findings on the major parameters used in the Fiala Model and collated data used to define the passive system of the older person leading to the development of the Typical Older Person.

4.2 The existing Fiala model body parameters (Passive System)

The passive system constitutes the different components of the human body which makes up the body structure and determines the weight of a person. This is composed of different sets of tissues that perform different functions. Lean tissues comprising (muscle and organs) are metabolically active but fat (adipose) tissues are not (Quinn, 2012). The non-fat component which is referred to as the fat free mass serves as the structural and functional component of the human body and consists of around 72% of water 21% protein and 7 % bone minerals (RRI, 2012). The fat tissue component of the human body consist of about 20% water and 80% adipose tissue and is referred to as the fat mass (RRI, 2012). Muscles in the lean tissues can be divided into three main groups comprising the skeletal, cardiac and the smooth muscle.

The passive system of the Fiala model consists of 15 spherical and cylindrical body elements comprising head, face, neck, shoulders, arms, hands, thorax, abdomen, legs, and feet and represents an average man with calibrated body parameters of body weight, percentage (%) body fat content, body surface area, basal metabolism rate, and basal cardiac output (Chapter 3). Table 4.1 shows the values of the parameters of the average person. Every cylinder and sphere was built of five (face, thorax and abdomen) or four layers (neck, shoulders, and the lower and upper extremities) which represents diferrent tissues materials comprising of the brain, lung, viscera, bone, muscle, fat and skin (Fiala, 1998).

Table 4.1 Passive system parameters

No.	Body Parameters	Unit	Average Person (Fiala Model)
1	**Body Weight (BW)**	kg	73.3
2	**Percentage Body Fat (PBF)**	%	14
3	**Height (H)**	m	1.72
4	**Body surface Area (BSA)**	m^2	1.86
5	**Basal Metabolic Rate (BMR)**	W	87
6	**Cardiac Output (CO)**	L/min	4.73

Fiala model simulates heat transfer that occurs in the body by blood circulation, metabolic heat production, conduction and accumulation whilst on the surface by convection, long and short wave radiation and evaporation of moisture from the skin (Fiala, 1998) see Chapter 3. In the design of the passive system for the typical older person anthropometric data was collated from published literature and used to replace the current data in Table 4.1. However, the formulation and segmentation of the human body in the Fiala model as reviewed in (Chapter 3) has been maintained.

4.3 Sensitivity test

The purpose of the sensitivity test was to evaluate and quantify the relative impact of individual parameters of the passive system of the Fiala Model. In conducting the sensitivity test, the various body parameters used in the development of the Fiala model's passive system were isolated and tested to see how varying one or the other affects the thermal balance of the body. This was to critically analyse and understand how they contribute to the sustainability or otherwise of the human bodies thermoregulation function. Cardiac Output (C.O.), Basal Metabolic Rate (BMR), Body Weight (BW), and Percentage fat Content (%F) were varied independently from -30% to +30%. These variations were used to carry out simulations involving the calculation of the neutral ambient temperature of a reclining human body and the results compared with the standard Fiala model. The unclothed resting human body was assumed to have an activity level at the basal metabolic rate (0.8met).

The required ambient air temperature at which the body can maintain a constant core temperature at 37.0°C without resorting to thermoregulatory actions was calculated. Compared to the reference condition, higher neutral temperature means that either the body was rejecting more heat than required to the environment or the body was producing less heat than normal. All the four parameters which were tested had different effects on the body's thermal behaviour in the thermo neutral environment. Figure 4.1 shows the representation of all the results of the predictions. From Figure 4.1, it can be observed that Basal Metabolic Rate has the most significant impact on the neutral temperature. As the human body ages, the effect of BMR is attenuated to some extent by the simultaneous reduction in cardiac output and body weight.

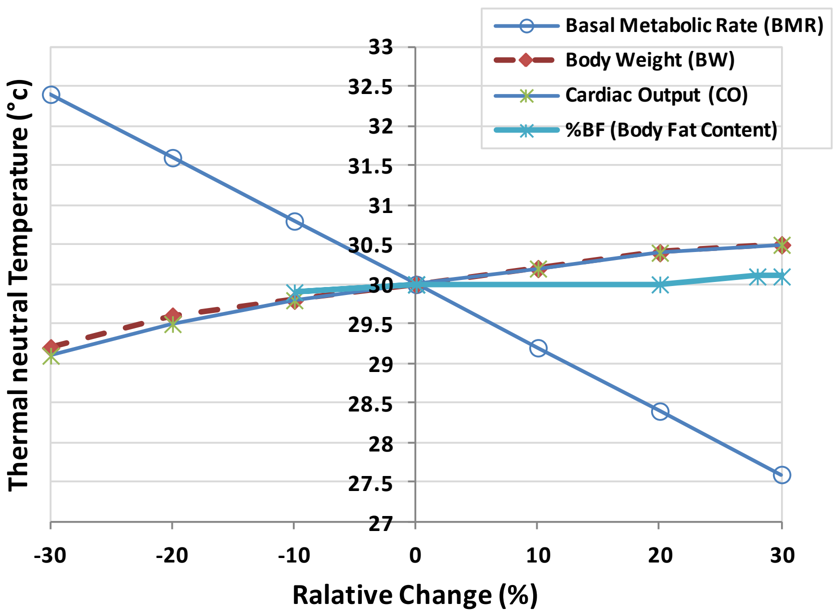

Figure 4.1 Sensitivity of thermal neutral ambient temperature

4.4 The typical older person

Fiala Model in its current form represents an average European adult male. To develop a model representative of the older population, an average age of reference for the older population which can be used to extract relevant experimental data was established. Indeed many studies have confirmed that there is no agreed definition of an older person but in general, those over 70 years of age are considered old and those between 21 and 40 years of age are considered young (Tinker, 2002). Those, who are between 40 to 70 years, are considered to be intermediate in age. However, many studies have included individuals who are 60 to 70 years as old (Wilson and Morley, 2003). Crews and Zavotka (2006) reported that, elders are frequently defined a persons aged 65 years and over and for health care and research purposes, these elders are subdivided into groups of young old (65 to 74 years), old-old (75 to 84 years) and oldest old (85+).

Review of literature on ageing research show many surveys, experiments and investigations on ageing and thermal comfort used varying age range of subjects. Foster et al. (1976) in studying the sweat responses in the aged used an older subject age of 70+ years, Collins et al.(1981) used 74.6 years in the study of urban hypothermia, preferred temperature and thermal perception in old age whilst Natsume et al. (1992) used an age range of 71 to 76 years in studying the preferred ambient temperature for old and young men in summer and winter. Kurz et al. (1993) had an age range of 60 to 80 years to define the older person. Even though some studies had within their ranges a starting lower age than 60 years, for example Frank et al. (2000b) used 55 to 71 years, Krag and Kountz (1950) used 57 to 95 years and Lind et al. (1970) used (39-53 years) an appreciable number had ranges well over 70 years. Table 4.2 provides a summary of 10 investigations and experiments where the age range varies from (60 to 89 years). In determining an average age of reference for the older population which can be used to extract relevant experimental data, the 2050 world projected population figures (Holtz-Eakin, 2005) (Figure 4.2) were used. The approximate calculated weighted mean age between 65 years to 100 years was 75 years.

Table 4.2 Older persons experiments

No.	Author/ Year	Age of Older subjects (years)	Title of Investigation
1	Collins et al.(1981)	**74.6**	Urban hypothermia: Preferred temp. and thermal perception in old age
2	Natsume et al. (1992)	**71-76**	Preferred ambient temperature for old and young men in summer and winter
3	Kurz et al. (1993)	**60 - 80**	The threshold for thermoregulatory vasoconstriction during nitrous oxide / isoflurance anesthesiais lower in elderly than in young patients.
4	Pierzga et al. (2003)	**64 - 75**	Delayed distribution of active vasodilation and altered vascular conductance in aged skin
5	Ogawa et al.(1993)	**68-78**	Thermoregulatory responses of old men to gradual changes in ambient temperature
6	Thompson-Torgerson et al.(2008a)	**61 - 77**	Altered neurotransmitter control of reflex vasoconstriction in aged skin
7	(DeGroot and Kenney (2007)	**65 - 89**	Impaired defence of core temperature in aged humans during mild cold stress
8	Bøkenes et al.(2009)	**62 - 89**	Annual variations in indoor climate in the homes of elderly persons living in Dublin, Ireland and Tromso, Norway
9	Krag and Kountz (1950)	**57 - 95**	Stability of Body Function in the Aged I Effect of Exposure of the Body to Cold
10	Krag and Kountz (1952)	**57 - 91**	Stability of Body Function in the Aged II Effect of Exposure of the Body to Heat

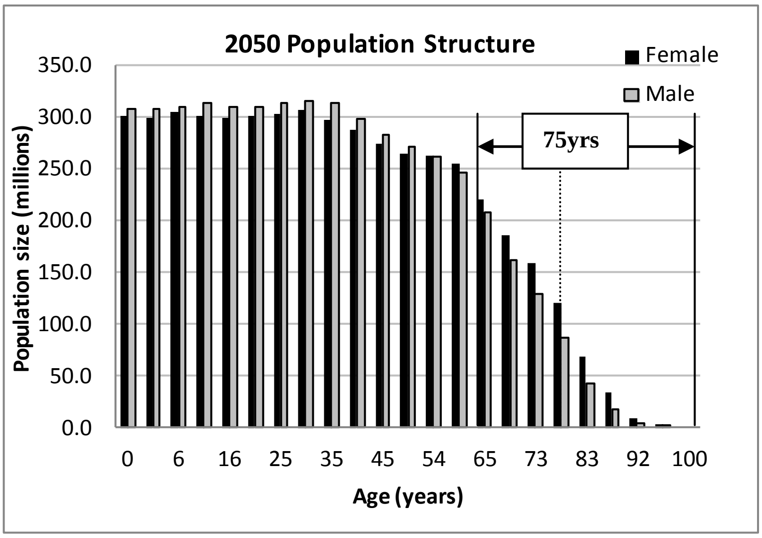

Figure 4.2 Population structure - 2050

However, in comparing the calculated age with the range of ages used in studies outlined in Table 4.2, it can be seen from Figure 4.3 that 75 years falls quite closely within the middle range of the ten (10) studies outlined and thus may conveniently be a fair representation of the typical older person.

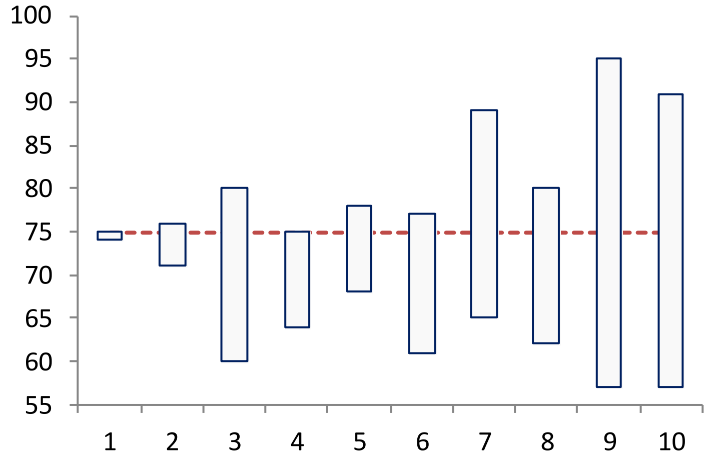

Figure 4.3 Graphical representations of older person's experiments

4.5 Body Weight (BW)

Body weight varies over the life span of humans with its attendant health implications. In men there is a gradual increase in weight up to age 55 thereafter they begin to lose it but in women weight gain continues up to 65 years after which they begin to lose it partly as a result of the loss of muscle tissue (Langan, 2010). Research conducted to establish the trend in age to weight reduction in the United States between years 1960 to 2002 revealed that after the age of 60 years there was a gradual decline in weight as shown in Figure 4.4 (Ogden et al., 2004). Between 20 to 29 years, average weight peaked at 77.25kg, increasing by 7.18% to 82.85kg between 40 to 49 years. At 75 years and over the measured weight was found to be 12.4% lower than the average value for 40 to 49 years reducing to 72.55kg. Barllet et al. (1991) found that average body weight of subjects both male and female peaked at 70.6kg between 16 to 18 years, however between 31 to 40 years there was an increase of 11.54% from the 16 to 18 years figure peaking at 78.75kg. Between to 66 to 86 years average weight was found to have reduced to 70.75kg representing a decrease of 10.16% (Figure 4.5).

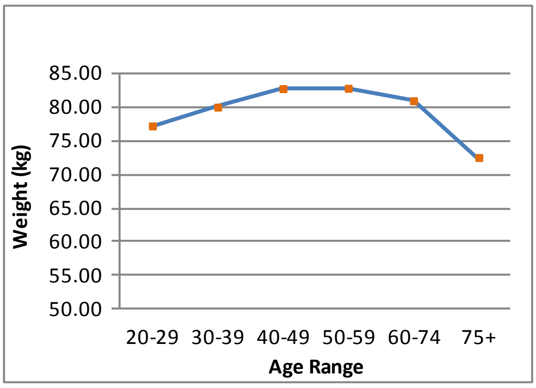

Figure 4.4 Average Body weight (Ogden et al., 2004)

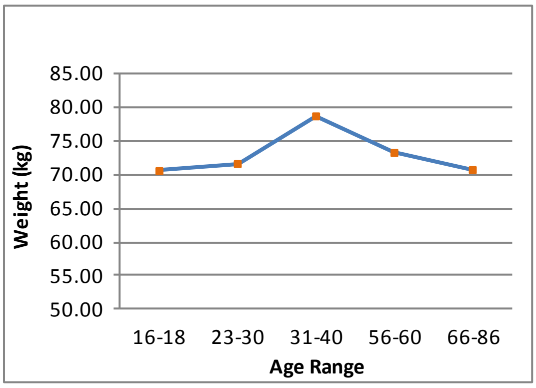

Figure 4.5 Average Body weight (Barllet et al., 1991)

Lazarus et al. (1998) studied the effects of body composition and fat distribution on the ventilatory function in adults consisting of both male and female subjects and measured body weight. They discovered that at the average age of 34.75 years, average weight was found to be 74.25kg. This figure however reduced by 5.2% to 70.4kg at 60.3 years (Figure 4.6). Krzywicki and Chinn (1967) investigated body density and fat of an adult male population as measured by water displacement with male subjects from ages 17 to 69 years. Measured body weight (Figure 4.7) show that between 30 to 34 years average body weight peaked at 85.8kg before falling over the years. Between 65 to 69 years average body weight was found to have decreased to 68.6kg representing a percentage reduction of 20%.

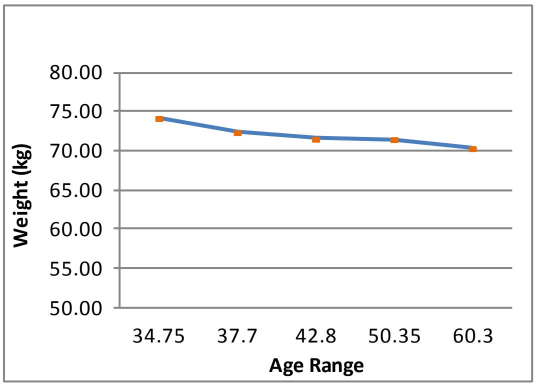

Figure 4.6 Average Body weight (Lazarus et al., 1998)

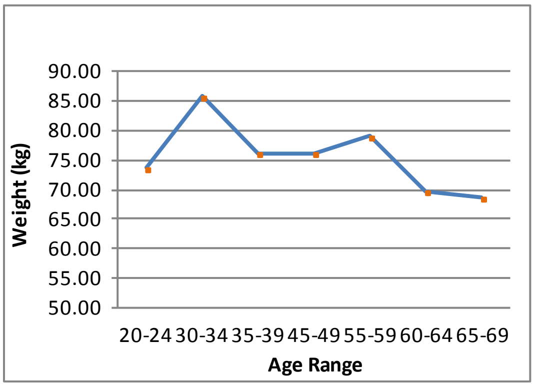

Figure 4.7 Average Body weight (Krzywicki and Chinn, 1967)

Paolisso et al. (1995) carried out an investigation looking at the body composition, body fat distribution and resting metabolic rate in healthy centenarians.

The study found that the peak weight at 50 years and below was 69.25kg and that of 100 years was 54.45kg representing 15.6% decrease (Figure 4.8). At age not more than 75 years the average weight was found to be 2.1% less than that of the 50 years and below.

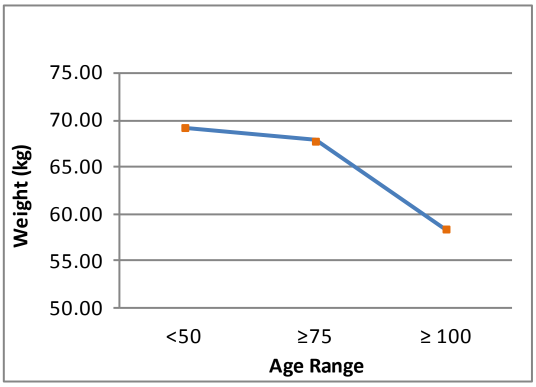

Figure 4.8 Average Body weight (Paolisso et al., 1995)

From the available experimental data, one issue which is undeniable is, with age there is an associated reduction in the weight of an individual. Literature reviewed differs on the percentage decrease in the weight but have all supported the fact that there is a reduction in weight as human's age. In developing a model for the older population, this information is critical in deciding on the weight of the typical average older person. Currently the Fiala model used 73.3kg as the representative weight of average person. In this research however, after critical review of available data sets, a new weight figure was extracted using the reference age of 75 years from the work done by (Ogden et al., 2004) see Figure 4.4. As such a percentage reduction of 12.4% was applied to the current value in the Fiala model for the older population. The resultant average weight for the typical older person is 64.2kg.

4.6 Percentage Body Fat

Whilst the weight of the body was found to be in decline after the age of 50 years, the percentage fat content in the body was found to increase with age. Paolisso et al. (1995) measured the fat content of subjects and found that the percentage (%) fat content of the body at age 50 years and below was 27.5% and that of age up to 75 years was 32.5% representing 18.2% increase (Figure 4.9). Barllet et al. (1991) found that, between to 31to 40 years percentage fat content was 29% but by 66 to 86 years, average percentage fat content increased by 15.3% see Figure 4.10.

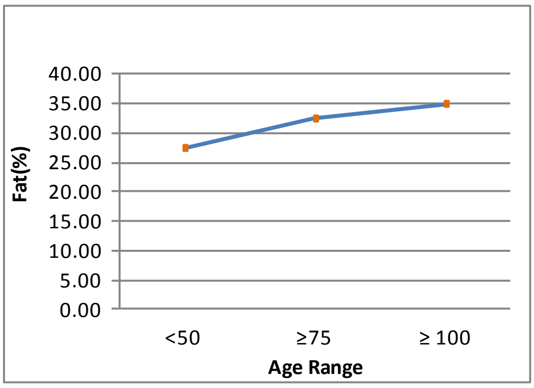

Figure 4.9 Average body fat (Paolisso et al., 1995)

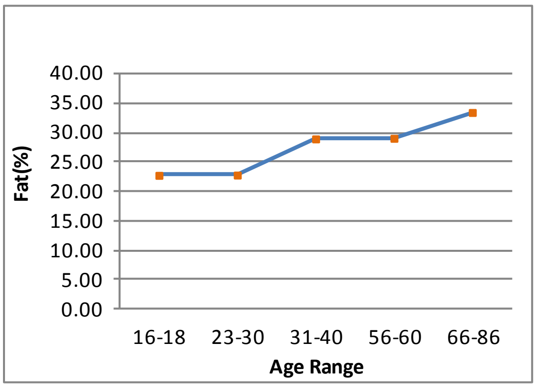

Figure 4.10 Average body fat (Barllet et al., 1991)

Chumlea et al. (1999) studied the total body water data for white adults aged 18 to 64 years. They measured the percentage fat content of subject aged between 30 to 39 years and found that body fat content was 36.2%. However, at age 60 years and above percentage fat content was found to have increased by 8.84 percent reaching 39.4%. Another study which found a rather large increase in the fat content of the subjects aged 17 to 69 years was carried out by Krzywicki and Chinn (1967) who investigated body density and fat of an adult male population as measured by water displacement with male subjects. Measured percentage fat content (Figure 4.11) show that between 30 to 34 years percentage body fat was 26.9% but by years 65 to 69, it rose to 38.7% accounting for a 44% increase.

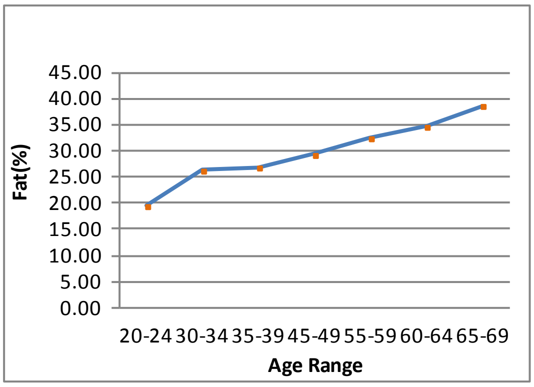

Figure 4.11 Average body fat (Krzywicki and Chinn, 1967)

Several studies have been conducted to measure the fat content of people and there are recommended values specified for a healthy fit person and persons considered to be obese. Table 4.3 shows the recommended percentage fat for men and women (Muth, 2009) and used by the American Council on Exercise (ACE).

Table 4.3 General Body fat Percentage Categories

Classification	**Women (%fat)**	**Men (%fat)**
Essential fat	10-13%	2-5%
Athletes	14-20%	6-13%
Fitness	21-24%	14-17%
Average	25-31%	18-24%
Obese	32% and higher	25% and higher

However, the above table’s values represent the average values for both males’ and females. In the design of a representative model for the older population, there is the need to extract the appropriate age adjusted body fat percentages which gives clarity on the percentages which apply to the older person. What is clear from the literature reviewed is, with ageing there is an appreciable increase in the fat content of the body. Work done by Gallagher et al. (2000) seems to be one of the key research works which critically looked at age and body fat percentages. Gallagher’s work has been adopted for use by several established institution including American College of Sports Medicine (ACSM) Guidelines 8th edition (ACSM, 2009) Table 4.4.

Table 4.4 Age-adjusted body fat for men and women

Women				
Age	**Underfat**	**Healthy Range**	**Overweight**	**Obese**
20-40 yrs	Under 21%	21-33%	33-39%	Over 39%
41-60 yrs	Under 23%	23-35%	35-40%	Over 40%
61-79 yrs	Under 24%	**24-36%**	36-42%	Over 42%
Men				
Age	**Underfat**	**Healthy Range**	**Overweight**	**Obese**
20-40 yrs	Under 8%	8-19%	19-25%	Over 25%
41-60 yrs	Under 11%	11-22%	22-27%	Over 27%
61-79 yrs	Under 13%	**13-25%**	25-30%	Over 30%

After a critical review and evaluation of the values of percentage fat increase over the years and with reference to the values used in the original Fiala model, the current research adopted a percentage fat content of 25% as the value for the typical older person. This value falls between the range for the healthy older man and woman Table 4.4. From available data, even the young person's percentage fat content is higher than the one used in the Fiala model. In the case of the older person's most of the values from literature points to a higher fat content than the current one selected. It can be observed from Table 4.4 that a value of 38.7% by Krzywicki and Chinn (1967) falls within the range of overweight same as that of Chumlea et al.(1999) which is 39.4%. As such 25% body fat content represents a reasonable percentage for the typical older person.

4.7 Height (HT)

Research has revealed that indeed as the human body ages, there is a relative decrease in height. Height reduction is largely attributed to the compression of the vertebra, flattening of the disks between the vertebra, loss of muscle mass and tone especially in the abdominal regions leading to poor posture and kyphosis (Villareal et al., 2005). Kyphosis is the curving of the spine that causes rounding of the back which leads to a slouching posture (ADAM, 2010). Research conducted by Lazarus et al. (1998) which measured body height in both male and female subjects revealed that at the average age of 37.7 years, average height was found to be 1.72m but this value however reduced at age 60.3 years by 5% to1.64m (Figure 4.12). Ogden et al. (2004) measured the height of 1,425 young subjects and 1,043 older subjects and discovered that between 30 to 39 years, the average height was 1.7m but this reduced by 75 years to 1.64 representing a 3.5% decrease (Figure 4.13).

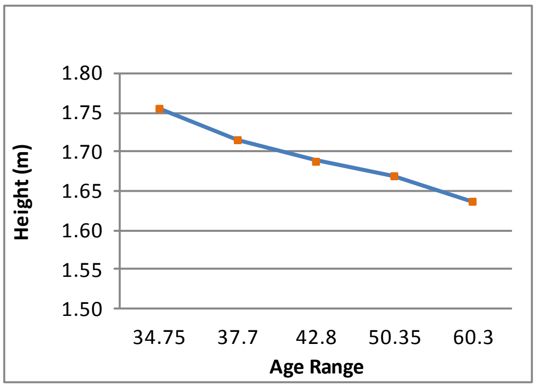

Figure 4.12 Average Body height (Lazarus et al., 1998)

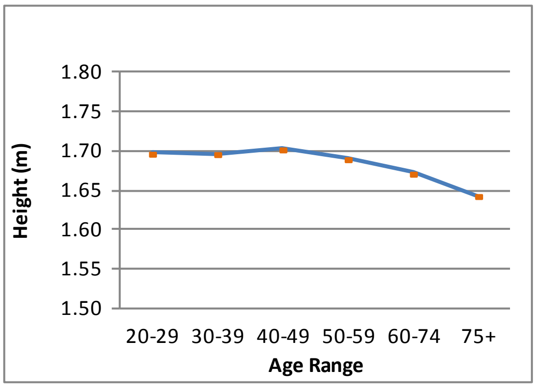

Figure 4.13 Average Body height (Ogden et al., 2004)

Barllet et al. (1991) also measured the height of test subjects between 6 to 86 years and found that, between 31 to 40 years average height was 1.72m but by 66 to 86 years average height reduced by 3% to 1.67m (Figure 4.14). Paolisso et al.(1995) found a 1.1% reduction in height of test subjects of aged less than 50 years (1.77m) and up to 75 years (1.75m) see Figure 4.15. Chumlea et al.(1999) however found a reduction of 1.7% in 30 to 39 years old subjects recording average height of 1.73m and 60 years and over recording 1.7m.

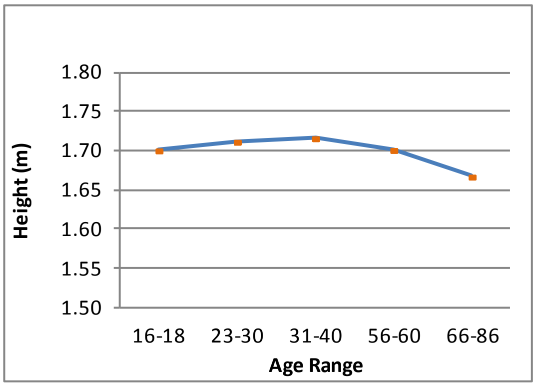

Figure 4.14 Average Body weight (Barllet et al., 1991)

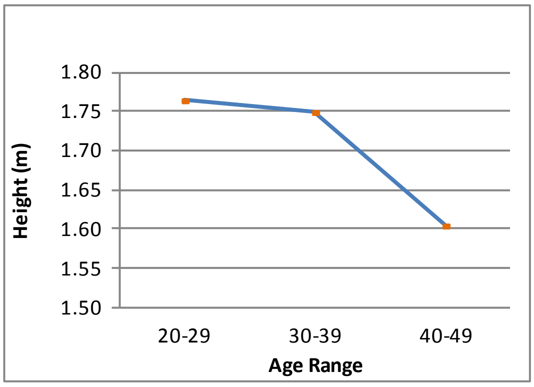

Figure 4.15 Average Body weight (Paolisso et al., 1995)

A longitudinal study titled *"the Baltimore Longitudinal study of Ageing"* (Sorkin et al., 1999) found that, average cumulative height loss from age 30 to 70 years was 3cm for men and 5 cm for women. However, by 80 years for men it increased to 5cm and for women to 8cm. In all literature reviewed, ample evidence exist that with ageing there are minimal reductions in the height of human beings. This is partly as a result of the compression of the vertebral bodies and kyphosis (ADAM, 2010 , Villareal et al., 2005).

It must however be noted that most of the older person used in these publications are from the older generation (centenarians). However it has been established in other published literature that new generation of humans are taller than the older generation. According to Dougherty (1998) the average height of people in industrialized nations over the last 150 years has increased to approximately 10cm. Therefore since the most likely use of the model is for future predictions the current research maintained the same figure used in the Fiala Model (1.72m).

4.8 Basal Metabolic Rate (BMR)

The rate of energy generation within an organism is defined as the rate of transformation of chemical energy into heat and mechanical work by aerobic and anaerobic metabolic activities (Yildirim, 2005). These activities are the sum of the biochemical processes by which food is broken down into simpler compounds with the exchange of energy (Yildirim, 2005). The minimum calorific requirement or energy which is required to sustain vital functions of the body at rest for its critical physiological upkeep including brain activity, breathing, heartbeat, and digestion (Schweiger-Whalen, 2011) is referred to as basal metabolic rate (BMR) or sometimes the resting metabolic rate (RMR). BMR forms the largest component of a person's daily energy expenditure accounting for 60 to 70% of total calorific needs (Schweiger-Whalen, 2011). As discovered in several literature reviewed, ageing in general has important impact on body composition which invariably also results in the reduction of basal metabolic rate (Elmadfa and Meyer, 2008). In order to determine the impact of age on BMR of humans various experiments and investigations have been carried out using the weight of organs in the body as reported in (Henry, 2000) and basal oxygen uptake of a person as reported in (Joseph et al., 1956).

Van Pelt et al. (2002) undertook an investigation looking at age-related decline in resting metabolic rate (RMR) in physically active men and sedentary men and observed a decline in both sedentary and physically active older men as compared to younger subjects. As shown in Figure 4.16, in the sedentary group of subjects, the resting metabolic rate of the young group (mean age 26 years) was 73.4 kcal/h but in the older group of subjects with mean age (62 years) the reported resting metabolic rate was 66 kcal/h representing a decrease of close to 10%. In the physically active cohort of subjects, the young group with mean age (27 years) had a resting metabolic rate of 75.4 kcal/h whilst the older group of subjects with mean age (63 years) had a resting metabolic rate of 65.8 kcal/h representing a decrease of 12.5% (Figure 4.17).

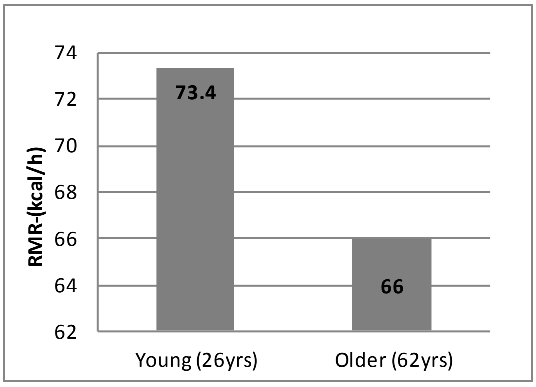

Figure 4.16 RMR Sedentary (Van Pelt et al., 2002)

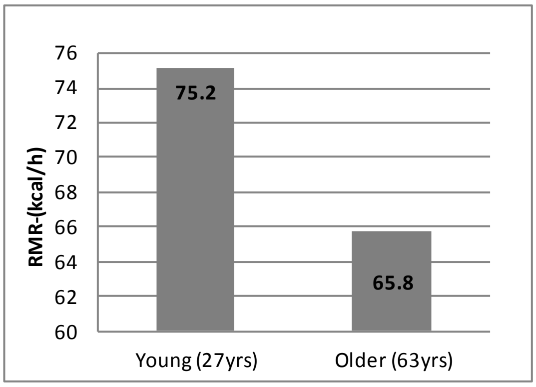

Figure 4.17 RMR Physically active (Van Pelt et al., 2002)

Frisard et al.(2007) investigated ageing, resting metabolic rate and oxidative damage and found a relative decline in metabolic rate. In subjects of age between 20 to 34 years, the metabolic rate was found to be 1587 kcal/d whilst 60 to 74years subjects had 1465 kcal/d. In subjects aged up to 90 years, the metabolic rate was found to be 1165 kcal/d which amounts to a 27% decline from the young group 20 to 34 years (Figure 4.18). Work done by Aub-Du Bois which has been extensively reported in (Bruen, 1930, Henry, 2005, Henry, 2000), points to a reduction in the BMR of humans as a result of age with young subjects between 20 to 29 years reporting a BMR of 38.25 (Cal/m^2/h) whilst older subjects aged between 70 to 79 years had a BMR of 34.25 (Cal/m^2/h) representing a 11% reduction (Figure 4.19).

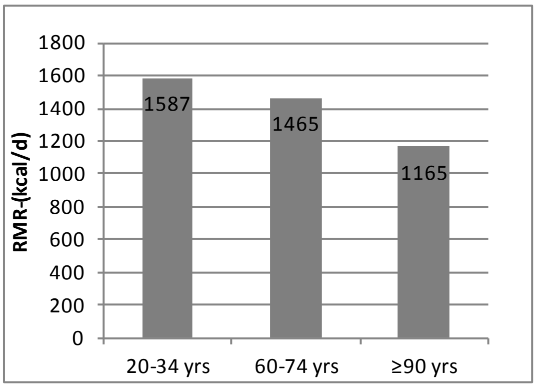

Figure 4.18-RMR (Frisard et al., 2007)

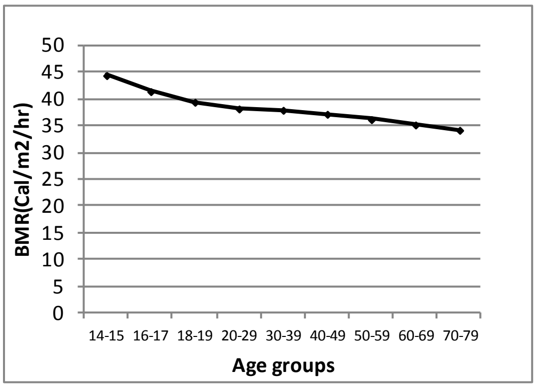

Figure 4.19 BMR- Aub Du-Bois (Bruen, 1930)

According to the Oxford database as reported in Henry (2005) there is also a reduction in the BMR with regards to age when measured in relation to the weight of a person. Henry (2005) compared the findings of the Oxford BMR and that of Food and Agriculture Organization/World Health Organization/United Nations University (FAO/WHO/UNU)-(FAO BMR) and found that whilst the two agreed that with age there is a decline in BMR, there exist differences in their respective predictions. Oxford BMR for age group of 18 to 30 years at weight 75kg was 79.4W whilst for age group above 60 years at weight 75kg the BMR was 69W representing a 13% reduction.

However for the FAO/WHO/UNU, the BMR between 18 to 30 years at weight 75kg was 82.9W whilst for age group above 60 years at weight 75kg the BMR was 69.3W representing a 16.4% reduction (Figure 4.20). Oxford BMR for age group of 18 to 30 years) at weight 65kg was 72.4W whilst for age group above 60 years at weight 65kg the BMR was 63.3W representing a 12.5% reduction. For the (FAO/WHO/UNU) BMR, 18 to 30 years at weight 65kg was 76W whilst for age group above 60 years at weight 65kg the BMR was 64W representing a 15.5% reduction (Figure 4.21).

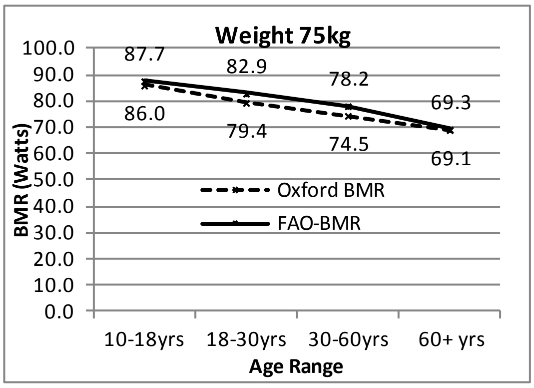

Figure 4.20 Average BMR (75KG) (Henry, 2005)

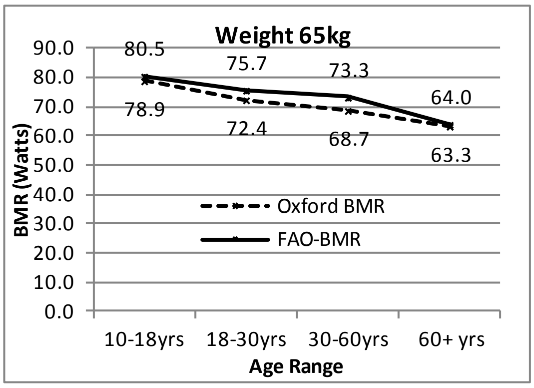

Figure 4.21 Average BMR (65kg) (Henry, 2005)

All the published results seem to contain significant amount of uncertainty due to the population samples and methods of measurement/estimation but collectively; they all show that ageing has effect on the Basal metabolic rate of humans. Work done by Aub-Du Bois reported in (Bruen, 1930, Henry, 2005, Henry, 2000) has been used as a reference BMR in many age related BMR calculations. Drawing inferences from data sets from the Oxford BMR and FAO/WHO/UNU BMR which reported quite similar values of at weight 75kg for older persons (69W and 69.3W respectively) and (63W and 64W respectively) at the weight of 65kg, the current research adopted the value of 64W as the BMR value for the typical older person.

4.9 Cardiac Output (CO)

Cardiac responses as well as other body parameters are altered as a result of the effect of chronological age. During quiet supine rest, cardiac output tended to be lower in the older men (Taylor et al., 1992). Work done by (Brandfonbrener et al., 1955) also confirms a significant link between ageing and reduction in cardiac output see Figure 4.22.

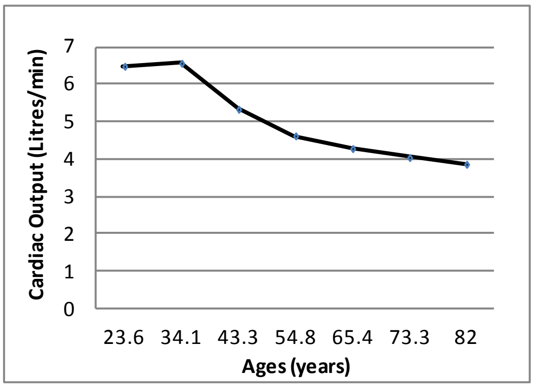

Figure 4.22 Average Cardiac Output (Martin Brandfonbrener, 1955)

At an average age of 43.3 years the average cardiac output measured was 5.347L/min whilst at 73.3 years; cardiac output was found to have reduced to 4.05L/min. But according to Abrass (1990), the subjects used in the Brandfonbrener et al.(1955) study were not screened for occult coronary artery disease reporting that the results tend to be different (Lakatta et al., 1987) when subjects were first screened for occult coronary artery disease (Rodeheffer et al., 1984). Rodeheffer et al. (1984) found in their study that whiles heart rate decreases with age, resting cardiac output is unaffected during rest and when subjects undertook exercise. However Julius et al.(1967) in their work looking at the influence of age on the hemodynamic response to exercise stated that older subjects had a lower resting cardiac output than normal subjects (Julius et al., 1967).

Payton and Poland (1983) reported on the work of Rockstein and Sussman in 1979 which reveals a decrease in cardiac output from approximately 5.0 L/min at age 20 years to 3.5 L/min at age 75 years representing a 30% decrease. Payton and Poland (1983) points out that cardiac reserve is also found to have decreased with age thus diminishing an individual’s ability to respond to physical or psychological stress. Taylor et al. (1992) found in young and older men that cardiac output and stroke volume were lower (Figure 4.23 and 4.24). Cardiac output of the Older subjects was 23.1% lower than that of the younger subjects whiles the stroke volume was 23.4% lower.

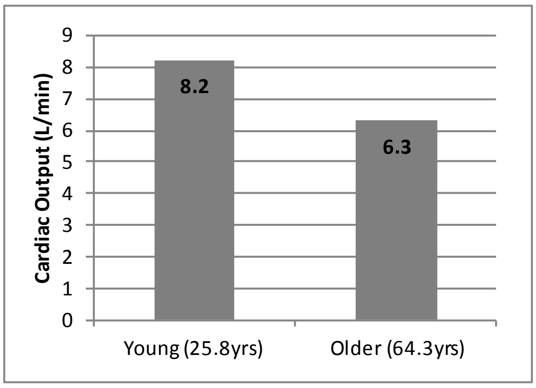

Figure 4.23 Cardiac Output (Taylor et al., 1992)

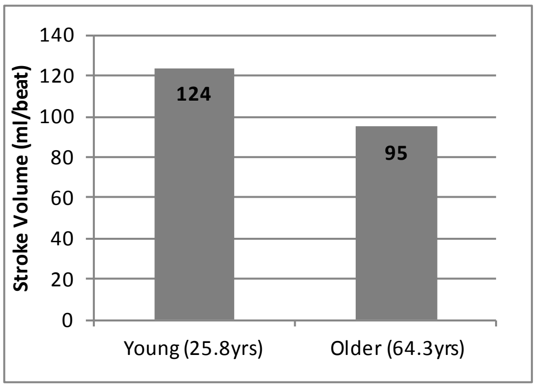

Figure 4.24 Stroke volume (Taylor et al., 1992)

A°Strand et al.(1997) measured peak oxygen uptake and related variables of former education students during exhaustive exercise on treadmill 33 years after they were first tested and found that peak oxygen uptake and heat rate (beats per minute) reduced with age (Figure 4.25 and 4.26).

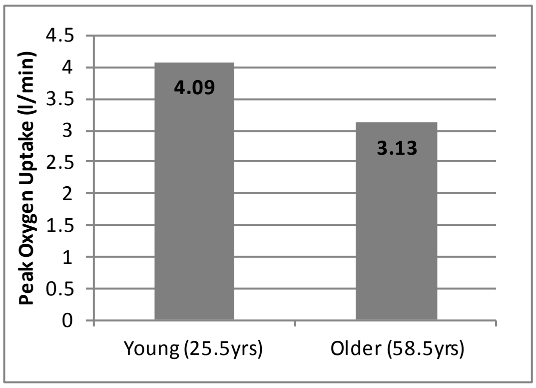

Figure 4.25 Peak oxygen uptake (A°Strand et al., 1997)

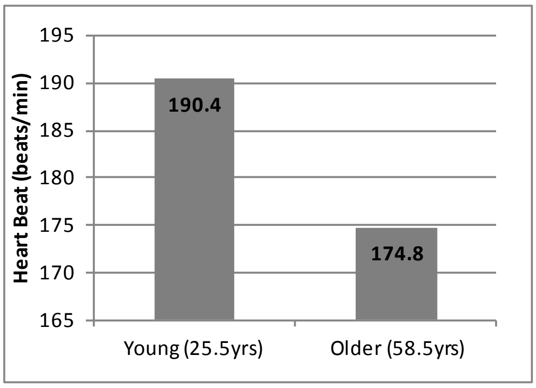

Figure 4.26 Heart beat (A°Strand et al., 1997)

Whiles agreeing with Abrass (1990) that there may be underlining health conditions which may contribute to the reduction in the cardiac output of the older person, there is also no denying the fact that other investigations have pointed out age related decline in cardiac output, peak oxygen uptake and heart rate in the older population (Brandfonbrener et al., 1955, Julius et al., 1967, Payton and Poland, 1983, Taylor et al., 1992, A°Strand et al., 1997). During passive heating Minson et al.(1998) found a decreased rise in cardiac output in older men as compared to young men (Figure 4.27) with an associated progressive fall in stroke volume in older men (Figure 4.28).

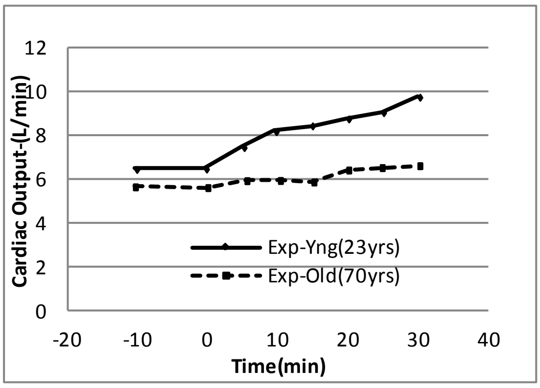

Figure 4.27 Cardiac Output (Minson et al., 1998)

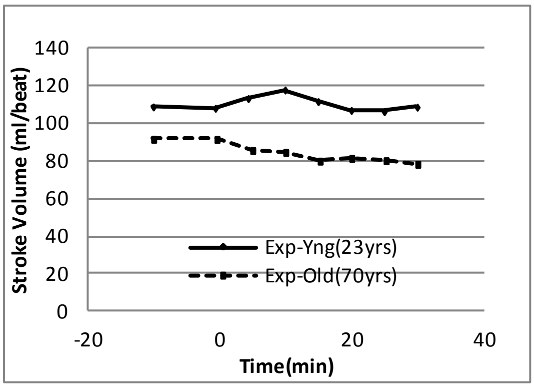

Figure 4.28 Stroke volume (Minson et al., 1998)

In concluding since the reference age for the typical older person is 75 years, data was extracted from work done by Brandfonbrener et al. (1955) where cardiac output was found to have reduced to 4.05 L/min in average age group of 73.3 years. As such 4.05L/min becomes the selected figure for cardiac output.

4.10 Modified Parameters

The values as in Table 4.5 were chosen as representative values for the typical older person passive system.

Table 4.5 Modified passive system parameters

No.	Body Parameters	Unit	Average Person (Fiala Model)	Typical Older Person	Change
1	**Body Weight (BW)**	kg	73.3	**64.2**	**-12.4%**
2	**Percentage Body Fat (PBF)**	%	14	**25**	**78.6%**
3	**Height (H)***	m	1.72	**1.72**	**0%**
4	**Body surface Area (BSA)**	m^2	1.86	**1.77**	**-5%**
5	**Basal Metabolic Rate (BMR)**	W	87	**64**	**-26.4%**
6	**Cardiac Output (CO)**	L/min	4.73	**4.05**	**-14.4%**

The values as proposed in Table 4.5 constitute an approximation of the ageing effect on the passive system parameters of the body. From literature reviewed, it was clear that ageing has effect on almost all body components. On body weight there is a progressive decrease after the age of 50 years with related increase in fat content of the body. The weight value adopted for the typical older person is 64.2kg with 25% fat content of the body as against 14% fat and 73.3kg used for the average person. The height of the typical older person is 1.72 the same as that of the average person and the calculated body surface area due to changes in body weight and fat content is ($1.73m^2$) as against $1.86m^2$. Basal metabolic rate for the typical older person is 64W with cardiac output 4.05L/min as against 87W and 4.73L/min for the average person.

4.11 Verification of the passive system of the Typical Older person

Verification is undertaken to ensure that the designed model has been built right and there are no errors or mistakes (Robinson, 1997). In reality no computational model can be fully verified, ensuring 100% error-free implementation (Macal, 2005, Robinson, 1997, Carson, 2002). To verify the new typical older person passive system, a thermo neutral test experiment was simulated. In this environment many published research works have suggested that, there is no active system function (that is in the thermo-neutral state the central nervous system function is relatively dormant).The verification process was to confirm whether the current parameters adopted for the older person, conform to established scientific findings. Many published research works points out that in thermo-neutral environments, the core temperature of older persons does not differ from that of the younger person. However for the body's peripherals for example the hands and feet, there is an appreciable variation in temperature between older persons and younger person (Rasmussen et al., 2001). This could be attributable to the reduction in basal metabolic rate as a result of decrees in muscle mass of the older person. In this verification procedure the test environment consisted of the following:

- Ambient temperature -Ta = 30°C
- Air velocity- va = 0.03m/s
- Relative Humidity - RH = 40%
- Activity level -act = 0.8met

Figure 4.29 and Figure 4.30 shows the predictions of the Fiala Model in comparison with Fiala Model with typical older person body parameters. For the rectal temperature (Tre) there is no difference between that of the average person and older person. However, for the mean skin temperature, variations between the predictions can be observed after 100 minutes into the exposure even though they are minimal.

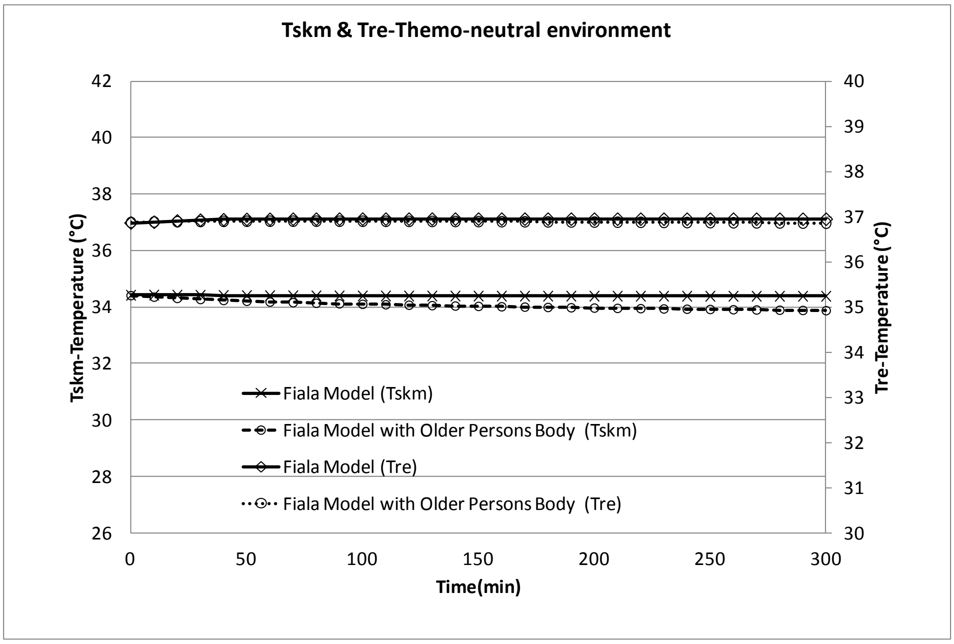

Figure 4.29 Mean skin and rectal temperature predictions

The mean skin temperature represents the summation of all the skin temperatures of the various body segments. Figure 4.30 show the results of the mean skin temperature profiles of the body's peripheral including hands, feet and arms.

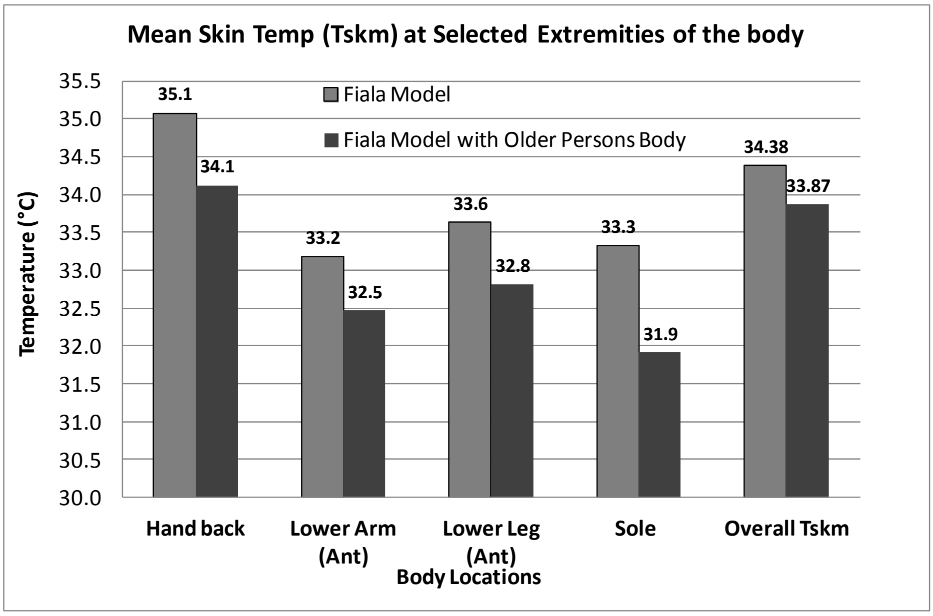

Figure 4.30 Skin temperatures of individual extremities

Skin temperatures of individual extremities, show varying degrees of older person's values being lower than that of the average person as predicted by the Fiala Model (Figure 4.30) which is in agreement with findings of Rasmussen et al.(2001). Clearly this is to be expected due to the reduction in many parameters of the body due to ageing including reduced basal metabolic heat generations, reduced muscle mass and increased fat deposition. The trend of the predictions confirms the findings from literature that when observed under thermo-neutral conditions the skin temperature at the extremities of the older persons is lower compared to younger persons. This therefore provides a reasonable justification to conclude that the changes made to the passive system of the Fiala Model resulted in a fairly functional modified model with body parameters of older person.

4.12 Summary

This chapter explored the passive system of the Fiala model leading to the development of a new passive system for the typical older person. In doing this;

- Sensitivity analysis was conducted on the major body parameters used in the Fiala model where Basal Metabolic Rate (BMR) was found to have the most significant impact on thermo-neutral temperature.
- A representative age was established for the typical older person to aid in data extraction for the modification process.
- Literature review was conducted on all the major passive system parameters and relevant and related data sets were extracted.
- New sets of modified parameters were developed for the passive system for the typical older person.
- These new parameters were verified in a simulation conducted for the thermo neutral environment, where the central nervous system (active system) is not activated and results of the verification show that at thermal neutrality, the skin temperatures at the extremities were lower in the older person as compared to the younger person.

Chapter 5 focuses on the development of the active system (Central Nervous System) incorporating the new passive system of the typical older person.

Chapter 5

Design of Active System of Older Person Model

5.1 Introduction

This chapter outlines some of the effect ageing has on the thermoregulation system (active system) of the human body and undertakes a review of the active system of the Fiala model. The chapter also provides experimental justifications for the modification of the active system to reflect that of the older person. It then introduces the algorithm used for the modification process and outlines the reasons for selecting such an approach. The chapter details the procedure adopted in implementing the selected method and the final results of the procedure.

5.2 Thermoregulation and Age

Thermoregulation refers to the ability of the body to physiologically adjust the body temperature in order to maintain a nearly constant core temperature around 37°C. This adjustment is controlled by the hypothalamus which is the thermostat centre of the body (Chapter 2). The hypothalamus receives information from temperature sensitive sensors in the various parts of the body about temperature variations in the body and integrates and compares it with a predetermined set point. An output command is then generated to energize an appropriate response in terms of heat production or conservation. In an exposure to cold conditions the body initiates responses to reduce the heat that is being lost to the environment and also generate heat internally by vasoconstriction and shivering respectively. However in exposure to heat the body initiates responses to dissipate the accumulated heat to the environment by means of vasodilatation and sweating (Chapter 2).

With age functional changes occur in the body which impact on the thermoregulatory system of the human body (Anderson et al., 1996). In reality, it results in the alteration of the older individual's response to variations in the ambient temperature. Figure 5.1 outlines the intrinsic effect of ageing on the body system and how it affects their response systems.

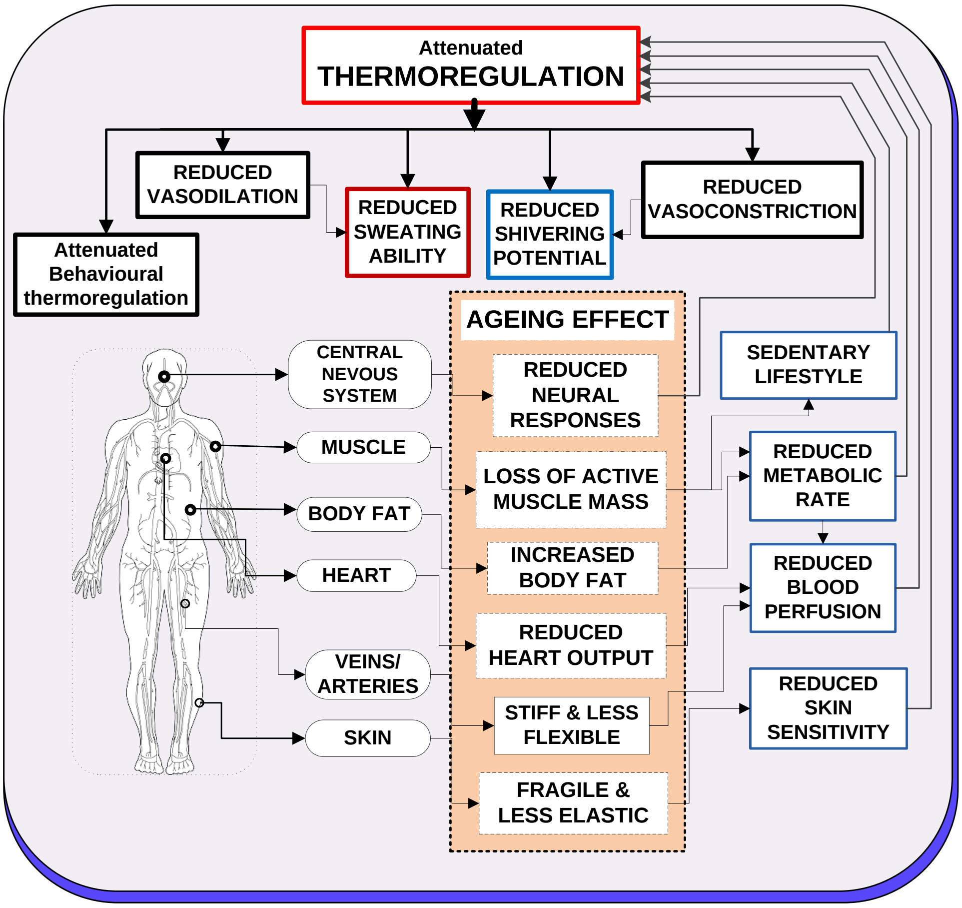

Figure 5.1 Ageing effect illustration

Reduced cardiac output (Taylor et al., 1992, Brandfonbrener et al., 1955), reduced muscle mass (Hyatt et al., 1990, Aniansson et al., 1986), reduce temperature sensitivity (Anderson et al., 1996), atrophy of skin (Nigam, 2008), reduced body weight (Ogden et al., 2004, Barllet et al., 1991, Lazarus et al., 1998), increase in body fat ((Paolisso et al., 1995, Chumlea et al., 1999) and reduction in basal metabolic rate (Henry, 2000, Van Pelt et al., 2002), are some of the effects of ageing. The spinal cord which serves as the backbone of the central nervous system is not immune to the age related decline in body properties. Esiri (2007) affirms that there was a gradual age-related loss of neural tissue up to 46% in humans over the age of 50 years. From the age of 20 to 60 years, neural losses are only around 0.1% per year but the process speeds up thereafter with reported cerebral blood flow decreasing by 20% (Joynt, 2000). The progressive loss of neurons and the associated reduction in impulse velocity and changes within the spinal cord typically leads to a slowing in reaction times (Spirduso, 1995). This can create problems for the older person on encountering painful or harmful stimuli. Neurotransmitters in the body also suffer age-related decline in their synthesis and receptors (Knight 2008). The peripheral nerve cells often show a progressive degeneration with age (Knight 2008) which results in the slowing of the conduction of nerve impulses by around 5 to 10% (Joynt, 2000). These depletions of the neurotransmitters and alterations in nerve density, electrophysiological and neurochemical properties of the afferent pathway to the brain (Blatteis, 2011) significantly alters structures and functions of the nervous system.

Indeed, all these changes affect how the older persons body responds in the event of thermal challenge either hot or cold stress. Some of the risk factors of the older person in response to heat include, increased threshold of sweating with diminished sweating response which has the likelihood of inducing heat accumulation in the older person's body. Other risk factors include reduced vasodilation and ability to adapt. These conditions are likely to expose the older person to thermal injuries including hyperthermia and heat stroke. In response to cold exposure, the likely risk factors of ageing effect include delayed onset of shivering, which has a high likelihood of causing drastic fall in the older person's core body temperature. Other risk factors include diminished shivering response and vasoconstrictions which may expose older persons to thermal accident including moderate to severe hypothermia.

5.3 Experimental Underpinning

One detailed experimental trial carried out to examine the effects of ageing on the thermal behaviour of the human body with regards to the threshold at which shivering and sweating begins in both young and older persons was undertaken by Anderson et al.(1996). In the study, skin temperature was kept constant by the immersion of subject's in pre-conditioned water. The core temperature variation which does not initiate thermo-effector activities was defined as the passive temperature liability. The magnitude of this process, specifically the range between the thresholds of shivering and sweating was termed the core temperature Null-Zone by (Mekjavic and Bligh, 1989). The ageing effect on the body and the performance of body system and organs sometimes cause a shift in the core temperature threshold for sweating and shivering. When this happens, the magnitude of the null-zone is affected. Drawing inferences from the works of (Bligh, 1973, Mekjavic and Sundberg, 1992) Anderson et al.(1996) proposed a theoretical representation of the impact of age on the width of the null-zone and the gain of the effector responses (Figure 5.2).

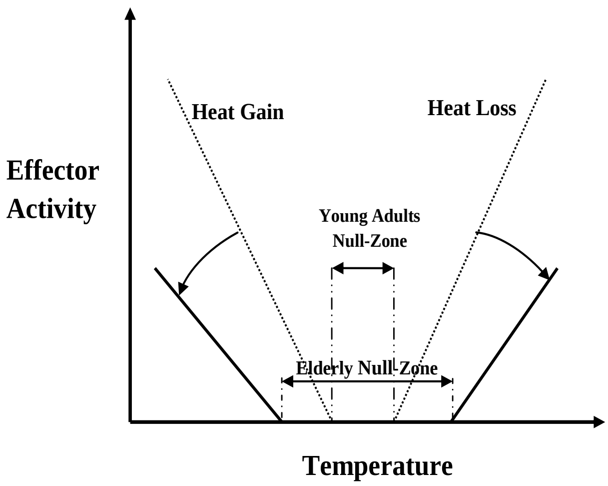

Figure 5.2 Theoretical representation of the impact of age on the null-zone (Anderson et al., 1996)

Anderson et al.(1996) argues that whiles many studies have been conducted to examine the effect of age on the sweating and shivering potentials of the body under different experimental conditions for example, exposure to hot environments or exercises and immersion in cold water or exposure to cold air, skin temperature in these studies are varied. Also the rates of core heating and cooling have not been consistent and as such it was difficult to combine such studies to infer the effect of ageing on the passive temperature liability. In his study, the experimental set up was designed to compare the core temperature thresholds of shivering and sweating between elderly and young adults, ensuring that both thresholds are determined at:

- A constant skin temperature
- Identical rates of change of core temperature
- Similar directions of change of core temperature

It was hypothesized that by controlling these factors, the effect of age on passive temperature liability could be examined by comparing the magnitude of the null-zone between the elderly and the young adults. Further information about the test can be accessed from (Anderson et al., 1996). It was discovered after his experiment that, the change in tympanic temperature at which sweating abated was significantly greater in the elderly subjects than in the young adults (Figure 5.3). Also at the end of the experimental period, sweating rate was significantly lower in the elderly group as compared to the young adults (Figure 5.3). For Shivering, the change in tympanic temperature at the onset of shivering was significantly lower in the elderly as compared to the young adults (Figure 5.3). In analysing the results of the null-zone, the experiment lends credence to the theoretical diagram (Figure 5.2). The experimental results in Figure 5.3 show that, whiles the null-zone value for the young adults was [0.43 (0.14°C)] that of the elderly was [1.12 (0.39°C)]. Appendix C shows the detailed breakdown of individual tympanic temperature thresholds for cessation of sweating and onset of shivering and the magnitudes of the null-zone.

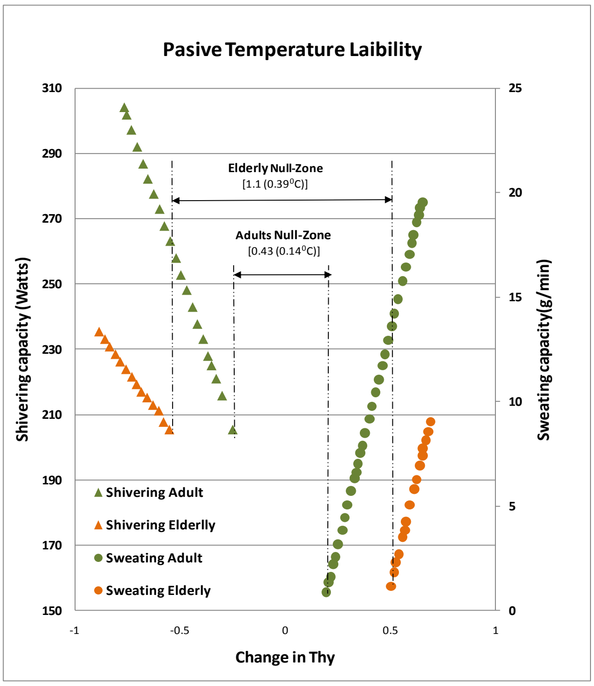

Figure 5.3 Age related changes in sweating and shivering responses.

Anderson et al.(1996) thus concluded that:

> *"there is a significant lowering of the tympanic temperature (T_{ty}) threshold for shivering while for sweating the (T_{ty}) threshold is significantly elevated. A consequence of these shifts in the thresholds of cessation of sweating (T_{sw}) and onset of sweating is the widening of the null-zone. Sweating rate attained during exercise in both groups were found to be significantly lower in healthy elderly subjects and the gain of shivering response significantly blunted in elderly individuals*".

Other extensive experimental trials were carried out by Kurz et al. (1993) in which thresholds for thermoregulatory vasoconstriction during nitrous oxide/isoflurane anaesthesia in patients were investigated. It was discovered that the thermoregulatory responses of the elderly were initiated at temperatures approximately 1.2°C less than that of the young adults (Figure 5.4). Another investigation carried out by Ozaki et al.(1997) looking at the threshold for thermoregulatory vasoconstriction during nitrous oxide/sevoflurane anaesthesia in the elderly concluded that thermoregulatory vasoconstriction and shivering are reduced in the elderly and taken together with available data, the elderly thermoregulatory defences against cold are activated at core temperatures approximately 1°C below that of the younger adults.

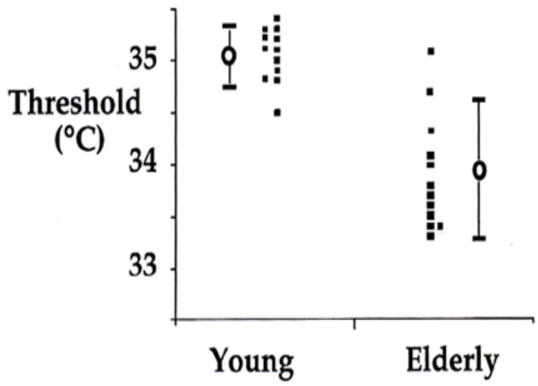

Figure 5.4 Vasoconstriction thresholds (Kurz et al., 1993)

Hellon and Lind (1956) observed the activity of sweat glands with reference to the influence of ageing and reported that older men have a delayed and attenuated sweating response with a reduced sweat production. During their experiment, it was discovered that the majority of older people took much longer time to start sweating than the young adults (Hellon and Lind, 1956). Foster et al.(1976) investigated the sweating responses in the aged using intradermal injection of acetyl choline and discovered a significant reduction in the sweating activity of the majority of older test subjects as compared to the younger ones and the body temperature threshold for the onset of sweating was also increased. These experimental studies provide ample evidence and proof of the degradation suffered by the active system and its response mechanisms as a result of the ageing phenomenon. These findings justify the need to further modify the active system of the model to reflect the behaviour of the older person.

5.4 The Active System of Fiala Model

The control equations for the active system were derived by non-linear regression analysis of several independent experimental scenarios which were chosen to specifically provoke active system responses in different environmental circumstances.
Table 5.1 shows detailed list of the individual coefficients implemented in equations 3.19 to 3.22. These equations can be represented by a general equation as shown in equation 5.1, where F represents the individual thermoregulatory responses including; Shivering – (SH), Vasoconstriction – (CS), Vasodilation – (DL), Sweating – (SW).

$$F = \langle A_1 tanh[A_2(T_{skm} - 34.4) + A_3] + A_4\rangle(T_{skm} - 34.4) + \langle B_1 tanh\left[B_2\left(T_{hy} - 37.0\right) + B_3\right] + B_4\rangle\left(T_{hy} - 37.0\right) + C\Delta T_{skm} * T_{skm} + D \quad (5.1)$$

Table 5.1 Fiala Model central nervous system control coefficients

	SH	**CS**	**DL**	**SW**
A1	10	35	21	0.8
A2	0.48	0.34	0.79	0.59
A3	3.62	1.07	-0.7	-0.19
A4	-10	-35	21	1.2
B1	0	0	32	5.7
B2	0	0	3.29	1.98
B3	0	0	-1.46	-1.03
B4	-27.9	0	32	6.3
C	1.7	3.9	0	0
D	-28.6	0	0	0

In running the model, results from the passive system simulation are needed which defines the setpoint of the state variables of (T_{skm}: 34.4°C) and (T_{hy}: 37.0°C).

With the setpoint temperatures, the active system can then be initialized. In all "*27 experimental scenarios by different authors involving a total of 279 human subjects each of whom was exposed repeatedly 8 experiments under steady-state conditions involving 163 subjects, and 19 experiments under transient conditions involving 116 subjects were used*" (Psikuta, 2009b). Regression analysis revealed that mean skin temperature ($T_{sk,m}$), and head core temperature (T_{hy}) affect regulatory responses in a non-linear fashion. The rate of change of the mean skin temperature ($dT_{sk,m}/dt$) was identified as a governing dynamic signal of thermoregulatory responses (Fiala et al., 2001, Fiala et al., 2010). Shivering (SH) has a theoretical maximum of 350W, vasoconstrictions (CS) has 600W/K and Sweating (SW) has 23 g/min (Fiala, 1998). As seen from Table 5.1 the coefficients when implemented in the control system equations enables the model to mimic the central nervous system behaviour of the average person. These coefficients need to be modified to represent the behaviour of the older person's active system.

5.5 Overview of the Approach to Model Fitting (modification)

This section outlines the steps adopted in modifying the active system of the Fiala model to represent the older person. Data from experimental studies was used to determine coefficients which could reflect the behaviour of the active system of the older person. The steps adopted include:

- Collection and analysis of data
- Selection of appropriate algorithm
- Use of Algorithm to carry out fitting
- Evaluating results from fitting procedure
- Selecting best fit coefficients for implementation.

5.5.1 Older person's experimental studies and complexities

Whilst there exist many research publications on the effect of hot and cold environments leading to hyperthermia and hypothermia in the elderly (Mercer, 2003, Basu and Samet, 2002, WHO, 2004, NIA, 2005, Collins, 1986) detailed experimental (chamber) study where the vital body parameter readings are measured as against changes or otherwise in the environmental temperature were hard to come by. This may be due to the fact that the cohorts of the population being considered older persons are quite sensitive, unique and complex. Some of these complexities may involve the recruitment of the right age range of subjects to be used for specific experimental trials (Chapter 4 sections 4.4). Furthermore being able to receive the consent of a reasonable number of subjects to be used for an experimental protocol (Wagner et al., 1974, Sagawa et al., 1988) is also an issue of concern. However in some cases, the elderly subjects are more than the younger subjects (Falk et al., 1994). Further to that in situations where the right age has been determined and a good number of subjects have given their consent to participate in the experiment, there is the problem of premature termination of the experimental protocol.

Mathew et al.(1986a) studied the influence of ageing on the thermoregulatory efficiency of man and used 15 subjects aged between 26 to 30 years for young persons and 15 subjects aged between 61 to 70 years for older persons. The study reported that, for the 2 hours experimental protocol set in an environmental chamber of temperature 10°C only the younger people were able to complete the experiment. Of the older persons who took part all of then withdrew from the experiment after 1 hour. Krag and Kountz (1950) carried out a study on the stability of body function in the aged looking at the effect of exposure of the body to cold of 8°C for duration of 120 minutes. Test subjects used included 6 subjects aged between 22 to 36 years for the young persons and 13 subjects aged between 57 to 91 years representing older persons. Krag and Kountz (1950) reported that at 90 minutes into the experiment 3 young subjects' representing 50% of the total withdrew from the experiment. At the end of the experiment only 2 subjects were left with a total of 4 withdrawing representing 66%. Of the older subjects, at 90 minutes into the experiment 9 subjects representing 69.2% of the total withdrew from the experiment. At the end of the experiment only 4 subjects were left with a total of 9 withdrawing representing 69.2%.

However, a study conducted by DeGroot and Kenney (2007) which looked at impaired defence of core temperature in aged humans during mild cold stress showed a different termination pattern. The test protocol involved a 20 minutes baseline period in an ambient temperature of 26.5°C followed by a steady reduction of the ambient temperature (Ta) at a rate of 0.25°C/min for 20 minutes, followed by another decrease of the (Ta) at a rate of 0.05°C/min for the reminder of the protocol up to 115 minutes . The protocol was terminated in subject when sustained involuntary shivering was reported by the subject or observed by the investigators. Test subjects used included 36 subjects aged between 18-30 years for the young persons and 46 subjects aged between 65-89 years representing older persons. DeGroot and Kenney (2007) reported that at 95 minutes into the experiment 21 young subjects' representing 58% of the total withdrew from the experiment whiles 33 older subjects representing 72% of the total withdrew from the experiment. At the end of the experiment at 115 minutes none of the young subjects were left representing 100% withdrawal whiles only 5 older subjects were left with a total of 41 withdrawing representing 89%. Whiles the above scenarios may be the case in some cases, other experimental studies (Smolander et al., 1990, Falk et al., 1994, Sagawa et al., 1988, Inoue et al., 1992, Krag and Kountz, 1952) may not have encountered these situations since their authors did not report on it.

This phenomenon invariably goes to reveal the homogenous nature of the older population group and the complexities involved in recruiting and using them for experimental trials. With that in mind diligent effort was made to select the relevant and most related sets of experiments and data sets. Indeed limited availability of experimental data set compelled the researcher to go futher back to 1950's to sieve through old published experimental results. As a result some of the data sets (13%) were populated from a range of experimental studies conducted in the 1950's but the majority (87%) came from between year 1990 to 2007. The published experimental data used for the calibration and validation of the older person model ranged from test cases with environmental exposures from 5°C to 42°C and varying work rates between 0.8met to 4.5met (Smolander et al., 1990, Falk et al., 1994, Sagawa et al., 1988, Inoue et al., 1992, Krag and Kountz, 1952, Krag and Kountz, 1950). Table 5.2 shows the list of 15 experiments involving a total of 163 older subjects used for the calibration of the active system of the model and for the validation of the complete model.

Table 5.2 Selected Experimental Data

Test Case No.	Author & Year	Type of Exposure	Subjects			
			Old		Young	
			Age (yrs)	No.(n)	Age (yrs)	No.(n)
1	**Falk et al.(1994)**	**Ta = 5 °C**	63.5	11	26.5	8
2	**Inoue et al.(1992)**	**Ta = 12 °C**	60-71	10	20-25	9
3	**Inoue et al.(1992)**	**Ta = 17 °C**	60-71	10	20-25	9
4	**Smolander et al.(1990)**	**Ta = 21 °C**	55 -60	6	28-37	8
5	**DeGroot and Kenney (2007)**	**Ta = 26.5 °C**	65-89	46	18-30	36
6	**Kenney and Armstrong (1996)**	**Ta = 28 °C to 10 °C**	61	6	26	6
7	**Smolander et al.(1990)**	**Ta = 30 °C**	55 -60	6	28-37	8
8	**Krag and Kountz (1952)**	**Ta = 42 °C**	57-95	14	21-32	12
9	**Krag and Kountz (1950)**	**Ta = 8 °C**	57-91	13	22-36	6
10	**Mathew et al.(1986a)**	**Ta = 10 °C**	61-70	15	31-53	15
11	**Potkanowicz et al.(2003)**	**Ta = 12 °C**	67.7	4	26.7	4
12	**Potkanowicz et al.(2003)**	**Ta = 18°C**	67.7	4	26.7	4
13	**Potkanowicz et al.(2003)**	**Ta = 27 °C**	67.7	4	26.7	4
14	**Sagawa et al.(1988)**	**Ta = 40 °C**	61-73	6	21-39	10
15	**Inbar et al.(2004)**	**Ta = 41.5 °C**	71	8	22.7	8
				163		**147**

5.5.2 Details of Collated test cases.

Test Case 1 - Response to rest and exercise in cold: effects of age and aerobic fitness (Falk et al., 1994).

Experimental Protocol: - The mean age of the Subjects age ranged from 63.5 years for the older group and 26.5 years for the younger group. Subjects wearing only shorts were exposed to 20 minutes of thermo-neutral condition with ambient temperature (Ta) of 22°C and relative humidity (RH) of 50% which includes 10 minutes of rest and 10 minutes of cycling at 4 met. The value for air velocity was not given as such 0.05m/s was used. Afterwards subjects rested for one hour in the same environmental temperature before being exposed to cold condition of ambient temperature (Ta) 5°C, relative humidity (RH) of 40% and velocity (va) of 0.05m/s. In the cold environment, subjects rested for 30 minutes and then exercised for another 30 minutes with load capacity equal to the one used in the thermo-neutral environment (4 met). Figure 5.5 shows the setup of the experiment.

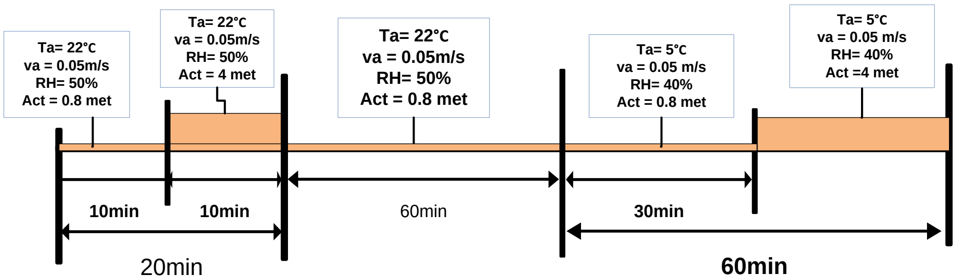

Figure 5.5 Experimental setup for test case 1

Test Case 2 - Thermoregulatory responses of young and older men to cold exposure (Inoue et al., 1992)

Experimental Protocol: This experimental protocol was set up to test subject's response to cold exposure of 12°C. The Older group of subjects ranged in age from 60 to 71 years and the younger group from 20 to 25 years. During the experiment, subjects wearing only swimming trunks sat on a chair in a comfortable environment with ambient temperature (Ta) of 28°C and relative humidity (RH) of 40% for at least 60 minutes, selected activity value was 1 met and velocity (va) was 0.1m/s. This period was referred to as the equilibrium period and during this time the measurement apparatus were attached to the subjects. After this the subjects stood and entered the environmental chamber and sat quietly for 60 minutes at ambient temperature (Ta) of 2°C, relative humidity (RH) of 45%, velocity (va) of 0.1m/s, activity rate of 1met. Figure 5.6 shows the setup of the experiment.

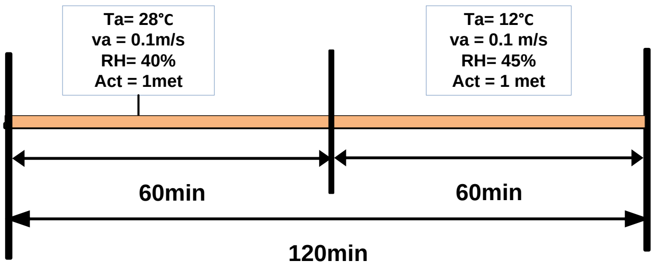

Figure 5.6 Experimental setup for test case 2

Test Case 3 - Thermoregulatory responses of young and older men to cold exposure (Inoue et al., 1992)

Experimental Protocol: The Experimental protocol for was the same as in Test Case 2 excepts after the equilibrium period, the subjects stood and entered the environmental chamber and sat quietly for 60 minutes at ambient temperature (Ta) of

17°C, relative humidity (RH) of 45%, velocity (va) of 0.1m/s and activity rate of 1met. Figure 5.7 shows the setup of the experiment.

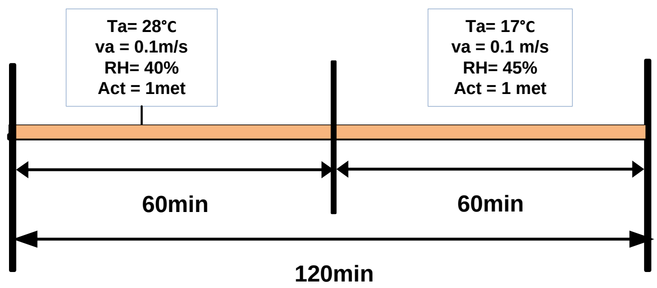

Figure 5.7 Experimental Setup for test case 3

Test Case 4 - Responses of young and older men during prolonged exercise in dry humid heat (Smolander et al., 1990)

Experimental Protocol: - The age of the Subjects age ranged from 55- 60 years for the older group and 28 to 37 years for the younger group. Subjects with clothing insulation value of 0.7clo relaxed in a thermo-neutral environment in a supine position for 30 minutes where measuring equipment's were attached. Thermo-neutral environment ambient temperature (Ta) was not given as such the selected value was 30°C, selected relative humidity (RH) of 50%, selected activity value of 1met, selected velocity of 0.1m/s. After this period subject then undertook a treadmill test in environmental exposure of ambient temperature (Ta) 21°C, relative humidity (RH) of 43%, velocity (va) of 0.3m/s and work (activity) of 2.5met. This treadmill test consisted of seven 30 minutes work periods interspersed by 5 minutes pauses for weighing rated at an activity value of 1met. The experiments ended with a cool off period of 30 minutes with environmental conditions similar to the ones in the thermo-neutral setup at the beginning of the test. Figure 5.8 shows the setup of the experiment.

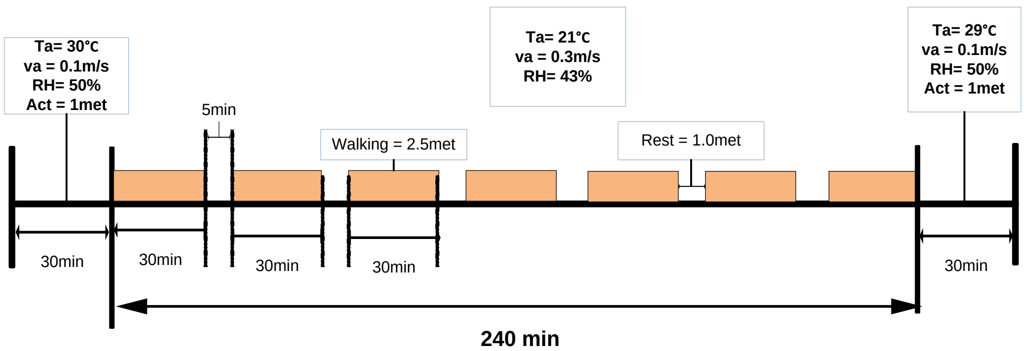

Figure 5.8 Experimental Setup for test case 4

Test Case 5 - Impaired defence of core temperature in aged humans during mild cold stress (DeGroot and Kenney, 2007)

Experimental Protocol: Thirty-six young subjects aged between 18 to 30 years consisting of 16 men, 20 women and 46 older subjects aged between 65 to 89 years consisting of 24 men, 22 women took part in the experiment. Subjects wearing shorts for men and shorts and bra for women entered the environmental chamber and stayed for a base line period of 20 minutes. The following were the thermo-neutral settings: ambient temperature (Ta) was 26.5°C, selected velocity (va) was 0.2m/s, selected relative humidity (RH) was 60%, and selected activity (resting) was 0.8met. After the baseline period, the ambient temperature in the environmental chamber (Ta) was steadily reduced at a rate of 0.25°C/min for 20 minutes followed by a decrease of 0.05°C/min for the reminder of the protocol. The protocol was terminated when sustained involuntary shivering was reported by the subject and/or is observed by the investigators. Figure 5.9 shows the graphical representation of the ambient temperature profile whiles Figure 5.10 shows details of the setup of the experiment.

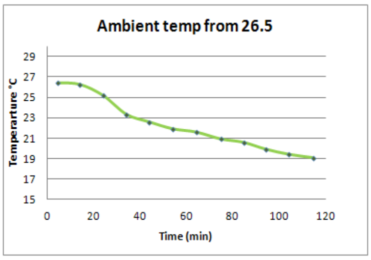

Figure 5.9 Ambient temperature representation

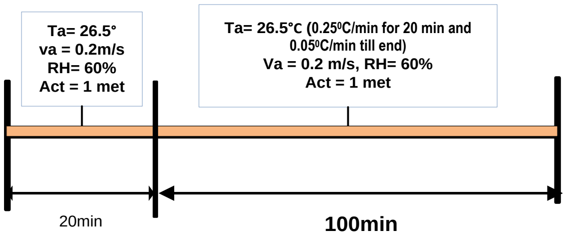

Figure 5.10 Experimental Setup for test case 5

Test Case 6 - Reflex peripheral vasoconstriction is diminished in older men. (Kenney and Armstrong, 1996)

Experimental Protocol: On arrival at the testing site, older subjects aged 58 to 67 years and young subjects aged 22 to 31 years were then instrumented, a clothing insulation of 0.6clo was worn. They then entered the environmental chamber were they sat comfortably in a semi-reclining posture for 120 minutes. Environmental conditions include: selected ambient temperature (Ta) of 28°C, selected velocity (va) of 0.5m/s, selected relative humidity (RH) was 60% and selected activity was 1met. The ambient temperature was controlled to ensure repeatability between subjects. The temperature was held at 28°C for the first 30 minutes followed by a systematic lowering over the next 40 minutes in steps of 2°C every 5 minutes. The ambient temperature was held constant at 10°C for the final 50 minutes of the test with air velocity, relative humidity and activity remaining constant. . Figure 5.11 shows the graphical representation of the ambient temperature profile whiles figure 5.12 shows details of the setup of the experiment.

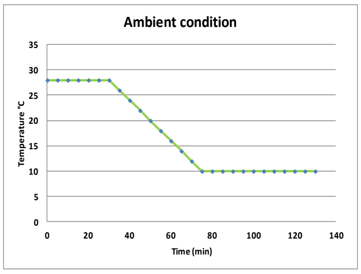

Figure 5.11Ambient Temperature representation

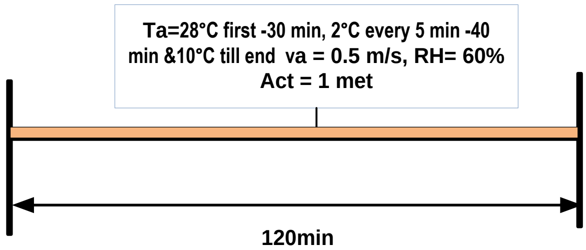

Figure 5.12 Experimental Setup for test case 6

Test Case 7 - Responses of young and older men during prolonged exercise in dry humid heat (Smolander et al., 1990)

Experimental Protocol: - The age of the subjects' age ranged from 55 to 60 years for the older group and 28 to 37years for the younger group. Subjects with clothing insulation value of 0.7clo relaxed in a thermo-neutral environment in a supine position for 30 minutes where measuring equipment's were attached. Thermo-neutral environment ambient temperature was not given as such the selected value was 30°C, selected relative humidity (RH) was 50%, selected activity value was 1met and selected velocity (va) was 0.1m/s. After this period subject then undertook a treadmill test in environmental exposure of ambient temperature (Ta) 30°C, relative humidity (RH) of 80%, velocity (va) of 0.3m/s and work (activity) of 2.5met. The treadmill test consisted of seven 30 minutes work periods interspersed by 5 minutes pauses for weighing rated at an activity value of 1met. The experiments ended with a cool off period of 30 minutes with environmental conditions similar to the ones in the thermo-neutral setup at the beginning of the test. Figure 5.13 shows the setup of the experiment.

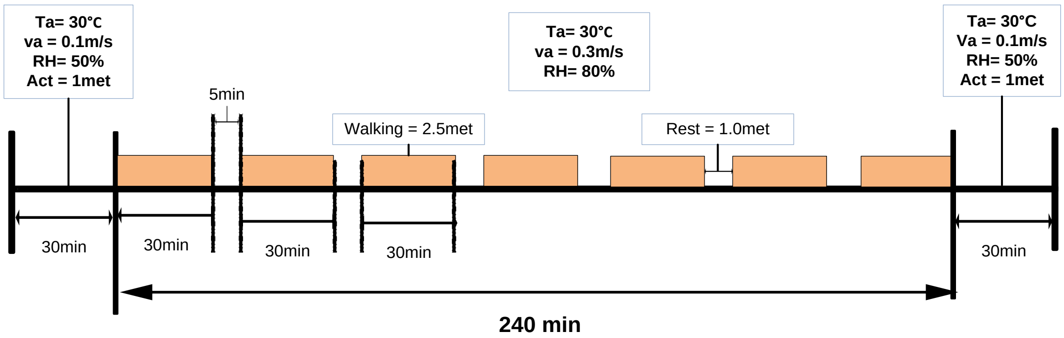

Figure 5.13 Experimental Setup for test case 7

Test Case 8- Stability of Body Function in the Aged II Effect of exposure of the body to heat (Krag and Kountz, 1952)

Experimental Protocol: - The age of subjects in this experimental ranged from 57 to 95 years for the older group and 21 to 32 years for the younger group. Subjects wearing shorts were observed under fasting basal condition where initial base line measurements were recorded. Environmental conditions include: selected ambient temperature (Ta) of 28°C, selected velocity (va) of 0.05m/s, selected relative humidity (RH) of 40% and selected activity (sitting) was 0.8met. After this period subjects were then moved to the experimental cabinet where the ambient temperature of the cabinet was set between the range of 38°C and 45°C, selected value was 42°C. Other environmental values include: velocity (va) of 0.05m/s, selected relative humidity (RH) was 100%; selected activity (sitting) was 0.8met. Figure 5.14 shows the setup of the experiment.

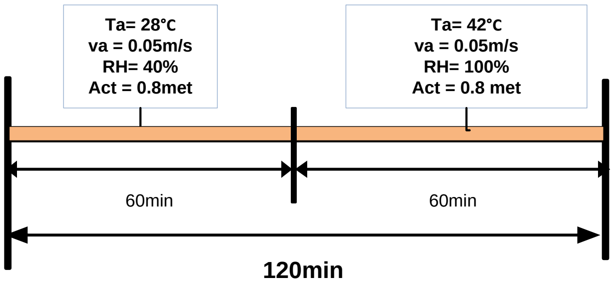

Figure 5.14 Experimental Setup for test case 8

Test Case 9 Stability of Body Function in the Aged I Effect of exposure of the body to Cold (Krag and Kountz, 1950)

Experimental Protocol: - The age of subjects in this experimental ranged from 57 to 95 years for the older group and 21 to 32 years for the younger group. Subjects were observed under fasting basal condition where initial base line measurements were recorded. Environmental conditions include: selected ambient temperature (Ta) of 28°C, selected velocity (va) of 0.1m/s, selected relative humidity (RH) of 70% and selected activity (sitting) of 0.8met. After this period subjects were then moved to the experimental cabinet unclothed (nude) where the ambient temperature of the cabinet was set between the range of 5°C and 15°C, selected value was 8°C. Other environmental values include: velocity (va) of 0.1m/s, selected relative humidity (RH) of 100% and selected activity (sitting) was 0.8met. Figure 5.15 shows the setup of the experiment.

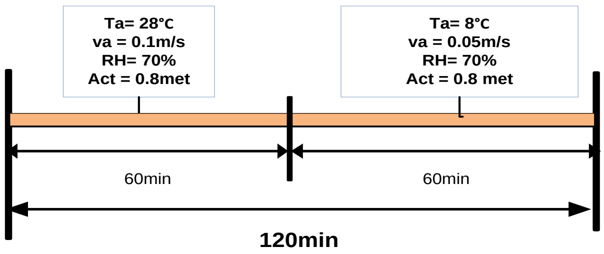

Figure 5.15 Experimental Setup for test case 9

Test Case 10- Influence of ageing in the thermoregulatory efficiency of Man (Mathew et al., 1986a)

Experimental Protocol: - The Older group of subjects ranged in age from 61 to 70 years and the younger group from 31 to 35 years. During the experiment, subjects dressed in shorts were made to relax in the thermo-neutral laboratory for one hour. The ambient temperature (Ta) of the laboratory was between 26 to 28°C, selected value was 27°C. Other environmental conditions include: selected velocity (va) of 0.1m/s, selected relative humidity (RH) was 50% and selected activity (sitting) was 1met. Afterwards subjects were then moved into a cold chamber with an ambient temperature (Ta) 10°C for 2 hours (120 minutes). Other environmental conditions include; velocity (va) of 0.3m/s, relative humidity (RH) of 40% and selected activity (sitting relaxed) was

0.8met. The elderly group of subjects stopped the test on the hour mark (60mins). Figure 5.16 shows the setup of the experiment.

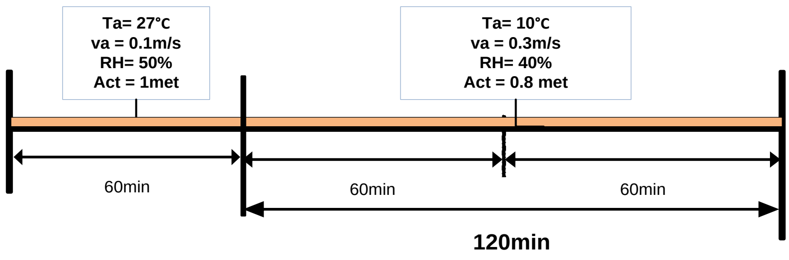

Figure 5.16 Experimental Setup for test case 10

Test Case 11- Age Effects on Thermal, Metabolic, and Perceptual responses to acute cold exposure (Potkanowicz et al., 2003)

Experimental Protocol: After instrumentation, both old subjects mean age 67.7 years and young subjects mean age 26.7 years rested for 30 minutes in a thermo-neutral environment outside the environmental test chamber. During this time, the baseline reading was collected. The subject's remained seated and still in a semi-reclined position on a plastic lawn chair with arms and legs separated and extended. Ambient temperature (Ta) was 29°C, selected velocity (va) was 0.1m/s, selected relative humidity (RH) was 45% and selected activity was 1met. After the baseline period the subjects while seated, were wheeled in the environmental test chamber where they remained for 120 minutes or when the core temperature reaches 35°C The ambient temperature (Ta) in the test chamber was 12°C, velocity (va) was 0.1m/s, relative humidity (RH) was 45%,and selected activity 1met. Figure 5.17 shows the setup of the experiment.

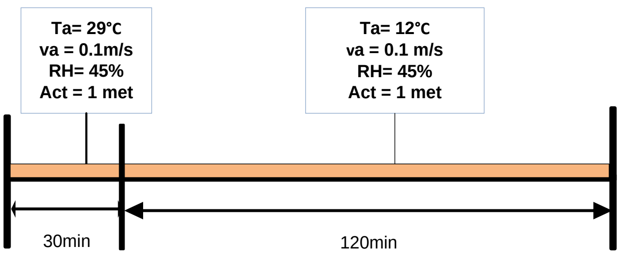

Figure 5.17 Experimental Setup for test case 11

Test Case 12 - Age Effects on Thermal, Metabolic, and Perceptual responses to acute cold exposure (Potkanowicz et al., 2003)

Experimental Protocol was the same to Test case 11 for the initial baseline setup but after the baseline period the subjects while seated, were wheeled in the environmental test chamber where they remained for 120 minutes or when the core temperature reaches 35°C. Ambient temperature (Ta) was 18°C, velocity (va) was 0.1m/s, relative humidity (RH) was 45% and selected activity was 1met. Figure 5.18 shows the setup of the experiment.

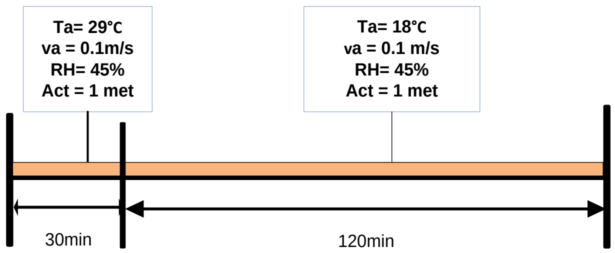

Figure 5.18 Experimental Setup for test case 12

Test Case 13 - Age Effects on Thermal, Metabolic, and Perceptual responses to acute cold exposure (Potkanowicz et al., 2003)

Experimental Protocol was the same to Test case 11 for the initial baseline setup but after the baseline period the subjects while seated, were wheeled in the environmental test chamber where they remained for 120 or when the core temperature reaches 35°C or when the core temperature reaches 35°C. Ambient temperature (Ta) was18°C, velocity (va) was 0.1m/s, relative humidity (RH) was 45% and selected activity was 1met. Figure 5.19 shows the setup of the experiment.

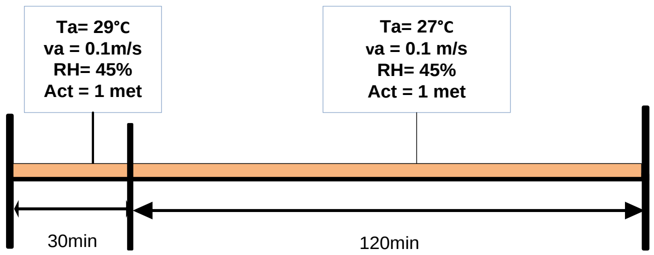

Figure 5.19 Experimental Setup for test case 13

Test Case 14 - Sweating and Cardiovascular responses of aged men to Heat exposure (Sagawa et al., 1988)

Experimental Protocol: The age of the subjects' age ranged from 61 to 73 years for the older group and 21 to 39 years for the younger group. Subjects dressed in shorts relaxed in the climatic chamber with ambient temperature (Ta) of 26°C with relative humidity (RH) of 40%, selected air velocity (va) was 0.1m/s and selected activity (sitting) 1met where the measurement apparatus were fitted. After the fitting of the apparatus subjects then sat for another 60 minutes (equilibrium period) with the same environmental conditions. After this period while the subjects remained seated, the room temperature was raised to 40°C with a constant relative humidity (RH) of 40%, air velocity (va) of 0.3m/s and activity value of 1met. Figure 5.20 shows the setup of the experiment.

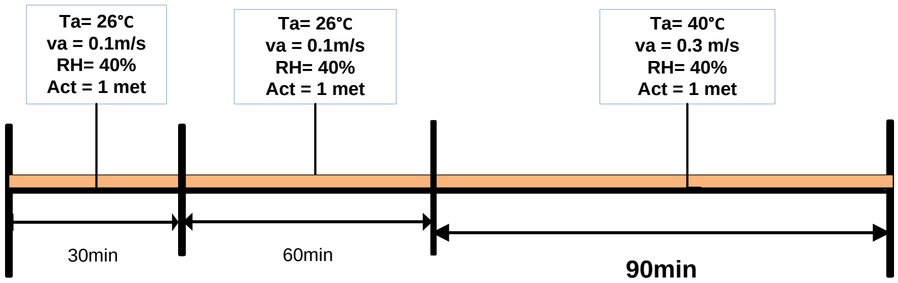

Figure 5.20 Experimental Setup for test case 14

Test Case 15 - Comparism of thermoregulatory responses to exercise in dry heat among prepubertal boys, young adults and older males (Inbar et al., 2004)

Experimental Protocol: Subjects for the experiment were aged 22.7 years for the young group and 71.0 years for the older group. Subjects rested in a thermo-neutral environment for 1 hour (60 minutes). Environmental conditions include; ambient temperature (Ta) of 29°C, relative humidity (RH) of 40%, selected air velocity of (va) 0.1m/s and selected activity (sitting) of 1met. Following this rest subjects then entered the climatic chamber. The climatic chamber protocol consisted of three 20 minutes bouts of exercise, followed by 5 minutes rest periods. Subjects exercised at a work rate of 50% of their V_{O2} peak. Total duration of experiment was 85 minutes or the test terminated when rectal temperature reached 39.1°C. Environmental conditions include; ambient temperature (Ta) of 41°C, relative humidity (RH) of 21%, selected air velocity (va) of 0.3m/s and selected activity was work and rest 1met and 2.5met. Subjects were dressed in shorts and shoes with clothing insulation value of 0.45 clo. Figure 5.21 shows the setup of the experiment.

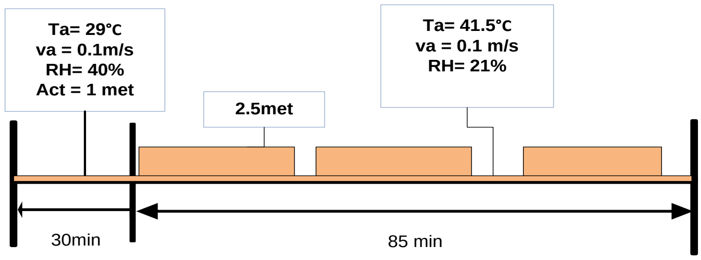

Figure 5.21 Experimental Setup for test case 15

5.6 Use of Algorithm

Critical review of the active system parameters (Table 5.1) and the data set extracted from selected published literature informed the researcher to adopt parameter calibration approach in arriving at the most appropriate sets of coefficients to use to represent the older persons active system. Parameter calibration is mostly used to bring computational predictions of a model into better agreement with measured quantities and this can be achieved by the use of various optimisation techniques (Thacker et al., 2004). Generally, optimisation techniques or processes involve the identification of the best fit parameter for a given system by adjusting a set of known parameters to enable simulation results to show the best agreement with the results acquired by experimental test (Guo, 2010). Indeed there are many optimisation algorithms available but they operate by the principle that, the optimisation process should minimize the objective function which is formed by the absolute value of difference between the simulated and experimental results at each time point (Guo, 2010).

5.6.1 Selection of Optimisation Algorithm

The current research selected an in house optimisation package based on the work of Zhang (2005) which aims at minimizing the root mean square error (RMSE) which is basically way of measuring how close a fitted line is to data points. In terms of model predictions, it is used to measure the difference between the results of a model and the measured experimental data of the same experimental test setting. The optimisation package operates by the principles of Genetic Algorithm (GA). Genetic

Algorithms (GA) are computer based search techniques patterned after genetic mechanisms of biological organisms and are the solution for optimisation of hard problems quickly, reliably and accurately (Malhotra et al., 2011).

Many researchers have validated its usefulness in solving optimisation problems and GA has gained a lot of popularity due to its ease of implementation and the robustness of its search and have been applied successfully in a variety of fields (Hoff et al., 1996, van Hoof et al., 2010). Genetic Algorithms are good at taking large, potentially huge search spaces and navigating them, looking for optimal combinations (Chakraborty, 2010). GA's is a search method used to find exact or approximate solutions to optimisation and search problems based on the evolutionary ideas of natural selection (Mulgund et al., 1998). According to Melanie (1998) in 1950s and 1960s, several computer scientists independently studied evolutionary systems with the idea that evolution could be used as an optimisation tool for engineering problems. Between 1960 and 1970's the concept of GA was invented and developed by John Holland, his students and colleagues at the University of Michigan. Improvements in computational power and technology have made Genetic Algorithms attractive for optimisation problems (Mulgund et al., 1998).

Genetic Algorithms (GAs) are direct search algorithms inspired by the process of evolution in nature, i.e. the natural selection based on the principles first laid down by Charles Darwin of the survival of the fittest (Guo, 2010, Mulgund et al., 1998, Bajpai, 2010). As such they represent an intelligent exploitation of a random search within a defined search space to solve a problem (Mulgund et al., 1998). In nature weak and unfit species within an environment are faced with extinction by natural selection and the strong ones have a greater opportunity to pass their genes to future generations via reproduction resulting in species carrying the correct combination in their genes becoming dominant in their population (Konak et al., 2006). Genetic Algorithms essentially manipulate chromosomes which are vectors of numbers or values and the chromosomes that produce the most suitable results are then selected to form the basis of a new generation of chromosomes (Randall, 1995).

5.6.2 Working Principles of Genetic Algorithm

All living organisms consist of cells and each cell contains the same set of one or more chromosomes that serve as a blue print for the organism and a chromosome can be conceptually divided in genes (Melanie, 1998). In Genetic Algorithms, the term chromosome typically refers to a candidate solution to a problem (Melanie, 1998). The simplest form of genetic algorithm involves three types of operators: selection, crossover, and mutation (Melanie, 1998). These operators simulate genetic evolution; attempting to achieve the best and adequate exploration of the design space and promote designs that are best adapted to the fitness landscape (Vavrina, 2008). The objective is that from an initial population of chromosomes containing random values within an acceptable problem defined limits, a solution or perhaps many solutions to the problem can be obtained after many generations have been formed (Randall, 1995). Figure 5.22 show the flow chart of a simple Genetic Algorithms.

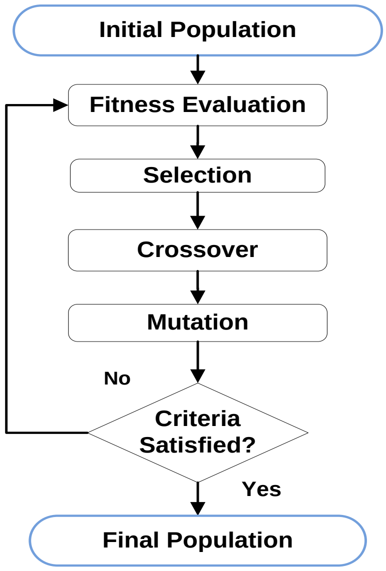

Figure 5.22 Basic Genetic Algorithm flow chart (Pathi, 2006)

5.7 Implementation Framework

Figure 5.23 shows the general framework of implementation reflecting the major steps adopted which has been divided into three main parts. Part 1 involves the evaluation and analysis of selected experimental data, Part 2 deals with the optimisation process and Part 3 shows process of model design.

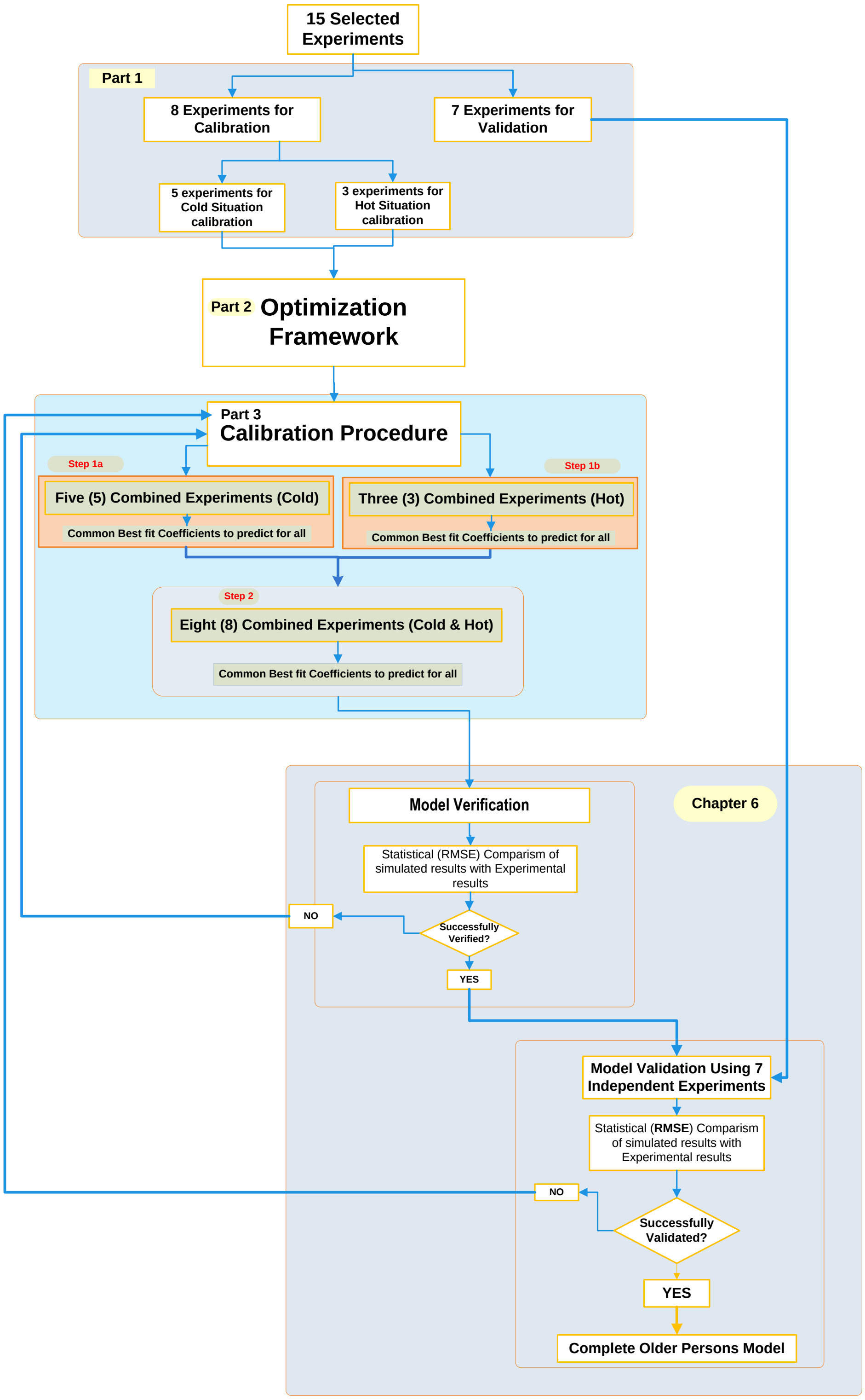

Figure 5.23 Framework of implementation

5.7.1 Part 1 Evaluation and analysis

The 15 selected experimental data sets were analysed and divided into two groups i.e. the calibration group (to be used for the modification process) and validation group (to be used to validate the completed model). Eight (8) experiments were in the calibration group and seven (7) experiments were in the validation group Table 5.3. From Table 5.3, it can be seen that most of the data focused on the core and skin temperature of the human body. These were used for the development of the active system of the older person with focus on the core temperature and mean skin temperature prediction of the older person. More attention was however deliberately placed on the core body temperature due to its importance in the analysis of the physiological and thermal state of the human body.

Table 5.3 Selected Experimental Data with further details

User Group	ID	Author & Year	Type of Exposure	Activity	Subjects				Results Used
					Old		Young		
					Age (yrs)	No.(n)	Age (yrs)	No.(n)	
Clalibration Data	C1	Falk et al. (1994)	Ta = 5 °C	Rest & Work	63.5	11	26.5	8	Tre
	C2	Inoue et al. (1992)	Ta = 12 °C	Sitting	60-71	10	20-25	9	Tskm, Tre
	C3	Inoue et al. (1992)	Ta = 17 °C	Sitting	60-71	10	20-25	9	Tskm, Tre
	C4	Smolander et al. (1990)	Ta = 21 °C	Walking/resting	55 -60	6	28-37	8	Tre
	C5	DeGroot et al. (2007)	Ta = 26.5 °C	Semi-recumbent	65-89	46	18-30	36	Tskm, Tesp
	C6	Kenney et al. (1996)	a = 28 °C to 10	Semi-reclining	61	6	26	6	Tskm, Tesp
	C7	Smolander et al. (1990)	Ta = 30 °C	Walking/resting	55 -60	6	28-37	8	Tre
	C8	Krag et al. (1951)	Ta = 42 °C	Sitting	57-95	14	21-32	12	Tre
Validation Data	V1	Krag et al. (1951)	Ta = 8 °C	Sitting	57-91	13	22-36	6	Tre
	V2	Mathew et al. (1986)	Ta = 10 °C	Sitting	61-70	15	31-53	15	Tskm
	V3	Potkanowicz et al. (2003)	Ta = 12 °C	Sitting	67.7	4	26.7	4	Tskm, Tre
	V4	Potkanowicz et al. (2003)	Ta = 18°C	Sitting	67.7	4	26.7	4	Tskm
	V5	Potkanowicz et al. (2003)	Ta = 27 °C	Sitting	67.7	4	26.7	4	Tskm
	V6	Sagawa et al. (1988)	Ta = 40 °C	Sitting	61-73	6	21-39	10	Tskm, Tesp
	V7	Inbar et al. (2004)	Ta = 41.5 °C	Work & Rest	71	8	22.7	8	Tskm, Tre
						163		147	

The eight (8) calibration experiments were further divided onto two sets Table 5.4. Set A for modifying the underlying equations which trigger a human body's response in cold exposure (vasoconstriction and shivering) and Set B for modifying the equations which trigger a the human body's response in hot environmental exposure (vasodilation and sweating). Set A includes test experiments of experimental chamber ambient temperature (Ta) exposure of 5°C, 12°C, 17°C, 21°C, 26.5°C whiles Set B includes 28°C 30°C and 42°C. Table 5.5 however lists the experiments of used for the validation of the model.

Table 5.4 Calibration Data set

User Group	ID	Author & Year	Type of Exposure	Activity	Test Conditions				Results Used
					Work rate	Velocity	Relative Humidity	Clothing	
Cold Calibration	C1	Falk et al. (1994)	Ta = 5 °C	Rest & Work	4 & 0.8 met	0.05m/s	40%	Shorts	Tre
	C2	Inoue et al. (1992)	Ta = 12 °C	Sitting	1met	0.1 m/s	45%	Swining trunks	Tskm, Tre
	C3	Inoue et al. (1992)	Ta = 17 °C	Sitting	1met	0.1 m/s	45%	Swining trunks	Tskm, Tre
	C4	Smolander et al. (1990)	Ta = 21 °C	Walking/resting	2.5 & 1.2 met	0.3m/s	43%	0.7 clo	Tre
Hot Calibration	C5	DeGroot et al. (2007)	Ta = 26.5 °C	Semi-recumbent	0.8 met	0.2m/s	60%	shorts-men/ shorts & bra-Female	Tskm, Tesp
	C6	Kenney et al. (1996)	Ta = 28 °C to 10 °C	Semi-reclining	0.8 met	0.5m/s	60%	0.6 clo	Tskm, Tesp
	C7	Smolander et al. (1990)	Ta = 30 °C	Walking/resting	2.5 & 1.2 met	0.3m/s	80%	0.7 clo	Tre
	C8	Krag et al. (1951)	Ta = 42 °C	Sitting relaxed	0.8 met	0.05m/s	100%	Shorts	Tre

Table 5.5 Validation Data set

User Group	ID	Author & Year	Type of Exposure	Activity	Test Conditions				Results Used
					Work rate	Velocity	Relative Humidity	Clothing Value	
Validation	V1	Krag et al. (1951)	Ta = 8 °C	Sitting	1met	0.1m/s	100%	nude	Tre
	V2	Mathew et al. (1986)	Ta = 10 °C	Sitting	1met	0.3m/s	40%	Shorts	Tskm
	V3	Potkanowicz et al. (2003)	Ta = 12 °C	Sitting	1met	0.1m/s	45%	Shorts	Tskm, Tre
	V4	Potkanowicz et al. (2003)	Ta = 18°C	Sitting	1met	0.12m/s	60%	Shorts	Tskm
	V5	Potkanowicz et al. (2003)	Ta = 27 °C	Sitting	1met	0.12m/s	60%	Shorts	Tskm
	V6	Sagawa et al. (1988)	Ta = 40 °C	Sitting	1met	0.09m/s	40%	Shorts	Tskm, Tesp
	V7	Inbar et al. (2004)	Ta = 41.5 °C	Work & Rest	0.8-4.5met	0.1-0.3m/s	21%	0.4 clo	Tskm, Tre

5.7.2 Part 2 Optimisation framework

Figure 5.24 shows the framework of the optimisation.

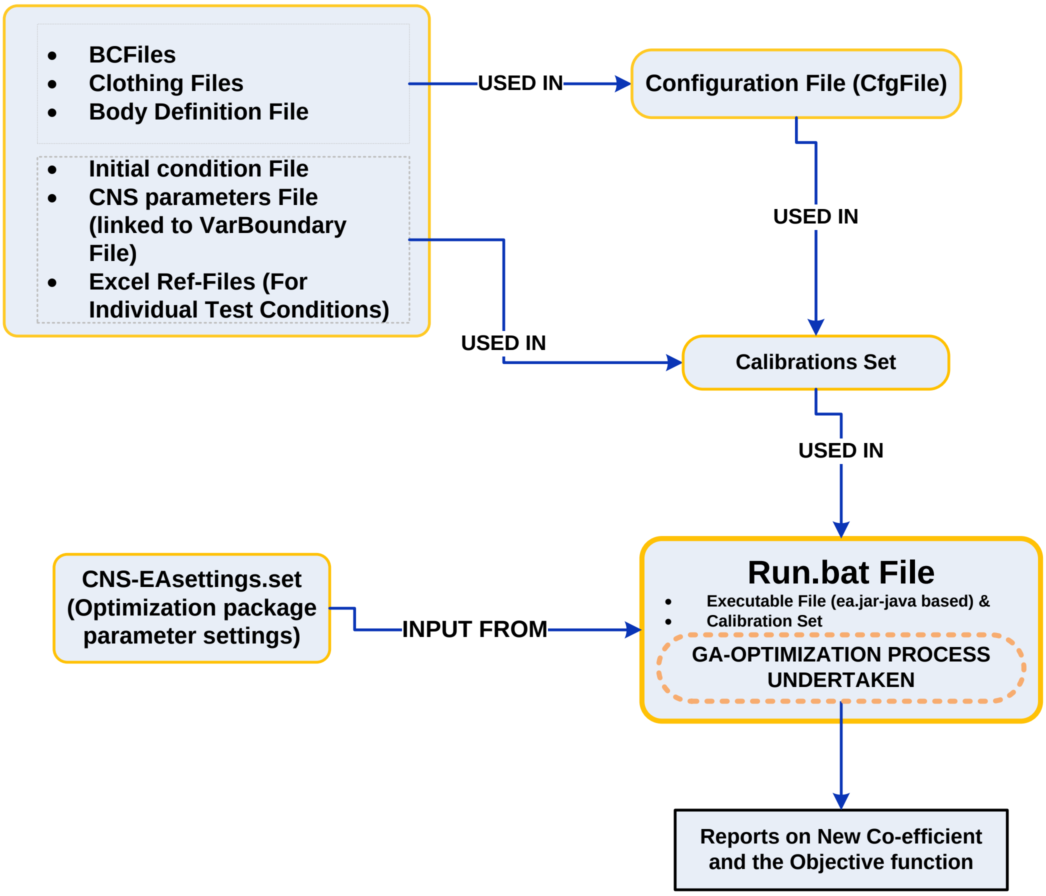

Figure 5.24 Optimisation framework

Preparation of the Input files

For each test condition input files were prepared based on the test conditions as specified in published literature.

- **Boundary conditions files (BCFiles)** this input file contains the time steps of the experiment, total duration of the experiment, the ambient temperature (Ta), the radiant temperature (wall temperature), air velocity, relative humidity and the work rate of the subject as extracted from published literature.
- **The body definition file** captures the details of body composition in this case the older person passive system data file which has been designed in Chapter 4.
- **Clothing insulation (Clo) file** contains details of the clothing subjects in the experiment being used wore as extracted from published literature.

- **Configuration file (Cfg-file)**- Incorporates the body definition file (in this case the older person passive system file), selected BCFiles relating to each experiment, clothing file related to each experiment and definition of appropriate output values to be reported in the output folder.
- **Initial conditions File** - In the initial condition file, variables which are set for each test conditions include the temperature of hypothalamus and means skin temperature (T_{skm}).
- **CNSparams files** setting, this file contains setting of the central nervous system parameters (these are the 40 co-efficient which define the active system and it is linked to the file (VarBoundaries) which contains the Upper and lower limits for the search space of the individual coefficients.
- **Excel Ref files**- constitute the extracted data sets from published literature for each of the test conditions being used for the calibration process. They represent either the mean skin temperature experimental values or the core temperature experimental values. These is what the optimisation model compares its outputs with whiles searching for the best fit coefficient.
- **Calibration Set file** – this file contains information on all the test cases to be simulated. It is load with the configuration file which has the boundary conditions files, clothing file and body definition file. It also incorporate in the Calibration set file is the initial conditions of each test case, including the central nervous system (active system) parameter file which is linked to the search space file (VarBoundaries). The prepared reference file (In excel csv.) for each test case is also uploaded to complete the set of parameters needed to carry out simulation for each test case. In the calibrations file, options are available to activate all the test cases and use for the optimisation run or only a few cases.
- **CNS-EA Setting file** – this file contains the settings of the optimisation model and defines the properties which enable it to carry out its search effectively. Table 5.6 presents a list of the properties in the chosen optimisation programme.

Table 5.6 Implemented Genetic Algorithms Property settings

No.	Name of Properties	Value of properties
1	Population Size	20
2	Number of Generations	200
3	Mutation Rate	0.1
4	Crossover Rate	1.0
5	Pop Replace	0.9
6	Choice of selection option	1/2 Tournament selector
7	Termination criteria	Number of generations

- **Run.bat File** – this file is loaded with executable file which is java based and the calibration set file. The run.bat file takes input from the CNS-EA Setting file in order to run the optimisation model.

Implementation of the Optimisation Process

Figure 5.25 presents the flow chart for the implementation of the GA for the optimisation of the Older Persons Model. This is the process which goes on inside the operations of the (run.bat file see Figure 5.24). To start the optimisation process, many individual solutions are randomly generated to form the initial population. In this case the population size of 20 (Table 5.6) was used. This population is generated randomly covering the entire range of possible solutions with the search space. In the process as specified below, once the GA process goes into the (evaluation process and reproduction process loop), until the termination criteria is satisfied the program shall keep running. In this case the termination criteria set is number of generations which is set at the beginning of the process.

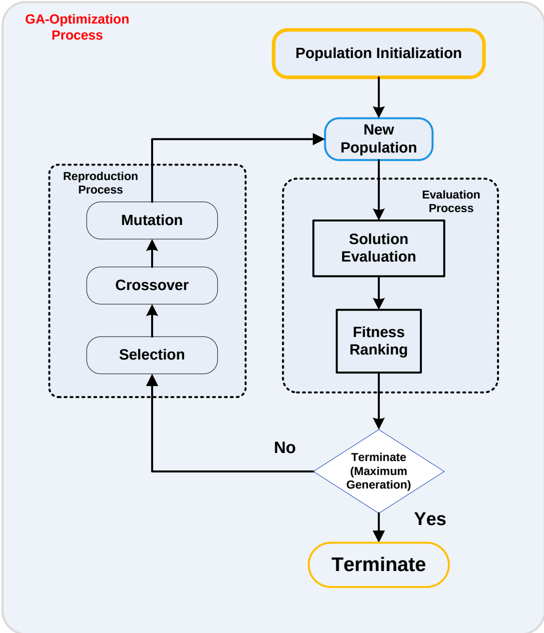

Figure 5.25 The Flow chart of Genetic Algorithm adapted with modification from (Zhang, 2005)

Evaluation Process - Evaluate individual Solutions

Each individual in the population is randomly evaluated based on their fitness using a fitness function. To evaluate a solution, randomly generated coefficients are implemented in the Fiala model and simulations carried out. As the thermal behaviour of the older persons is the main concern of this research, simulated values of the mean skin temperature and the core temperature in each experimental design condition is compared with the values extracted from published literature. The Fitness function measures how close the individuals fit the desired result. In this case how close the predictions of the mean skin temperature and core temperature are to the experimental data measured by the root mean square error (RMSE) between the experimental conditions and the simulated values.

5.8 Models Goodness of fit

Fitting models to experimental data sets will ultimately produce some results which may be identical to the system being modelled. But as to whether these results represent the true behaviour of the system being modelled needs to be investigated. It is possible to blindly treat model parameters found by the fitting procedure as valid (Stuart, 2011). Therefore in order to avoid making erroneous interpretations, it is necessary to inspect the results to ensure that it provides a suitable fit to the data and gives a realistic representation of the system being modelled (Stuart, 2011). In the ideal and most desirable situation, models should fit perfectly to the measured experimental data but this does not occur in most cases. As such, there is the need to have a measure of how well they fit. Indeed, there exist several metrics used for analysing goodness of fit of a model. In relation to this work, at this stage the author used the root mean square error (RMSE) in estimating the goodness of fit and this is described below.

5.8.1 Root Mean square Error (RMSE)

The root mean square error (RMSE) measures how close a models prediction is to measured experimental data of the same experimental test setting. RMSE seeks to aggregate into a single measure of predictive power the sum of squared errors of prediction and its formula is given as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - f_i)^2}{n}} \tag{5.2}$$

Where (y_i) is the observed value and (f_i) is the associated predicted value of the model.

5.9 Part 3 the Process of model design

Figure 5.26 shows the two major steps adopted to develop appropriate coefficients to be used for the elderly active system.

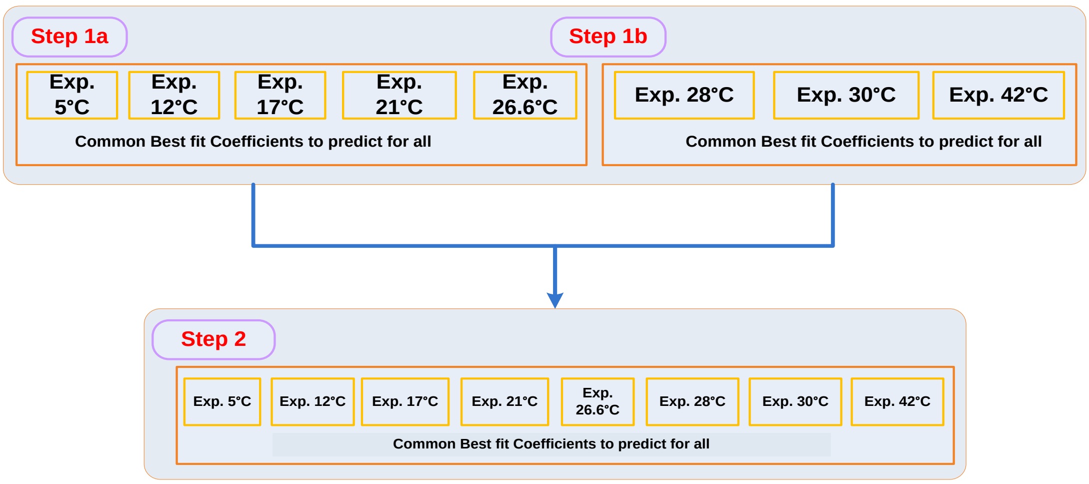

Figure 5.26 Framework of implementation all steps

5.9.1 STEP 1 Calibration

In order to obtain a reasonable agreement between experimental data and the older person's model predictions, the original parameters which form the basis of the control signals and which cannot explicitly be extracted from the available experimental data were calibrated. The calibration procedure involved the determination of the upper and lower limits of the search space for implementation in the optimisation programme. In this step the selected experimental conditions (Table 5.4) were divided into two groups i.e. Step 1a and Step 1b (Figure 5.27). Step 1a is a grouped representation of test experiments of (5, 12, 17, 21, 26.6) °C which are conditions related to the cold environments and have effect on the control signals of shivering and vasoconstriction.

Step 1b is a grouped representation of test experiments of (28, 30, 42) °C which are conditions related to hot environments and have effect on the control signals of sweating and vasodilation. Simulations were then carried out for each group and the resultant coefficient from each group implemented in the model. This was to establish a search space for step 2 which combines all the test cases in the optimisation simulation. Goodness of fit of the model predictions to the measured experimental data was evaluated using the root mean square error (RMSE).

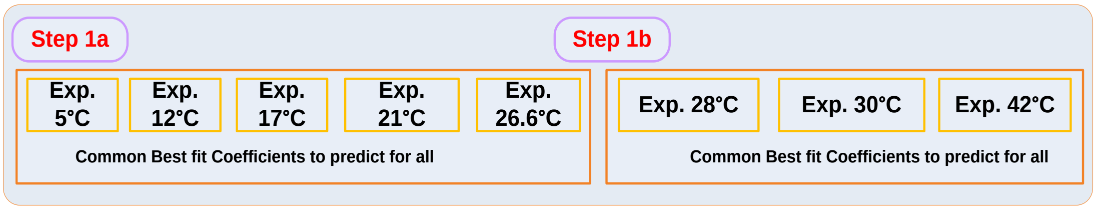

Figure 5.27 Framework of implementation step 1

Modification procedure

1. For each coefficient in Table 5.1, ranges of upper and lower numbers were randomly selected to form the search space for the optimisation programme.
2. Simulation runs were carried out for the optimisation programme to determine new sets of coefficient for both the cold conditions and hot conditions.
3. The new sets of coefficients were then implemented in the model and simulations conducted for each experimental test condition and the root mean square error (RMSE) calculated.

4. The trend of predictions of the model as compared to the available experimental data was studied.
5. Review of search results of the coefficients was conducted, for example where search results (coefficients were close to the lower or upper limit, that may be an indication of the search space not be wide enough).
6. After the review - search space was either increased or decreased and re-run of the optimisation programme carried out.
7. The new sets of coefficients were then implemented in the model and simulations conducted for each experimental test condition and the root mean square error (RMSE) calculated.
8. The trend of the results were studied once again and the process repeated for all test conditions.
9. Drawing on the trend of predictions the upper and lower limits which provide a reasonable search space for the optimisation model to work within were proposed.
10. This step was carried out iteratively until a reasonable agreement was found between the predictions and the experimental results measured by the numerical value of the RMSE with some modifications made to the search space settings if need be. The final search space values which produced small numerical error value (RMSE) was selected and implemented in step two which was the combination of all the test cases both hot and cold conditions.

Appendix D shows the results of the model predictions and Figure 5.28 and 5.29 shows the Root Mean Square Error (RMSE) for each test. Table 5.7 shows the details of the coefficients developed from step 1. It can be seen from figure 5.28 and 5.29 that, the calculated RMSE's reveal that, the optimisation method has the possibility of producing the expected results.

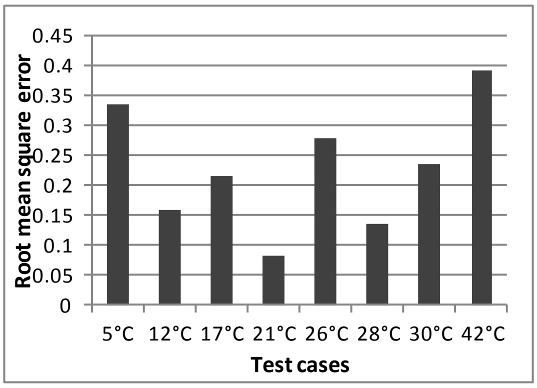

Figure 5.28 RMSE for core temperature

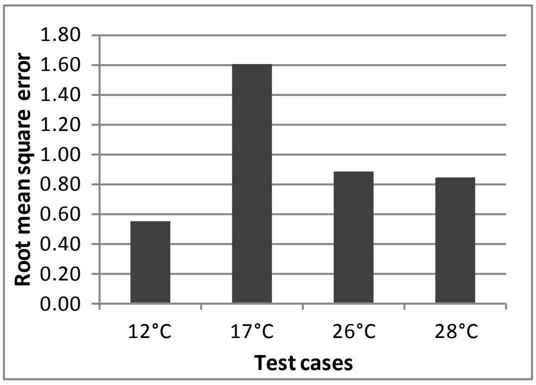

Figure 5.29 RMSE for mean skin temperature

Table 5.7 Coefficients generated from step 1

Coefficients			
SH	**CS**	**DL**	**SW**
15	28.1	23.5	2.1
0.2	4.9	2.3	0
1.4	4.2	0	-1.3
-1	-10	19.5	1.3
0	0	46.4	4.4
0	0	10	6
0	0	-3.5	-2.4
-28	0	13.6	1.1
1.7	4	0	0
-29	0	0	0

Table 5.7 shows the details of the coefficients generated from the implementation of step 1.

5.9.2 STEP 2-Implementation

Step two (Figure 5.30) was set up to bring all the test cases together for the optimisation simulation. This was to test whether the search space settings adopted could produce one set of coefficients which when implemented in the model can produce results which show good agreement with all the individual experimental conditions.

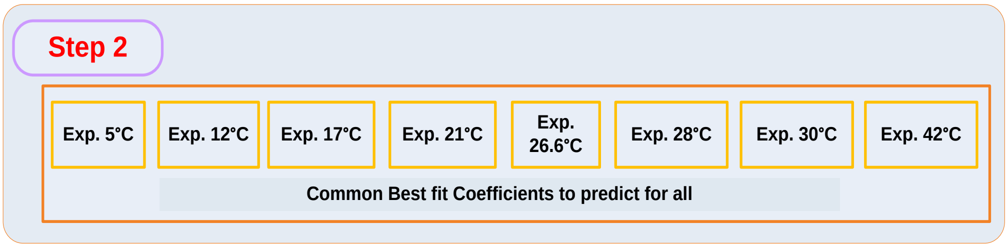

Figure 5.30 Framework of implementation Step 2

The grouped experiments were uploaded into the optimisation programme and several simulations were carried out. These were undertaken in the computer laboratory of De Montfort University (Institute of Energy and Sustainable Development). At each time of simulation, 10 computers simultaneously run the optimisation codes. The computers employed in the simulations process have the following processor specifications (Intel(R) Core(TM)2 Quad CPU Q6600 @ 2.40GHz 2.39GHz). It took not less than 6 hours for each optimisation simulation to be completed. Once the programme reaches the termination point, the researcher reviews the results and selects the new coefficients with the least RMSE for implementation in the model. Simulations of test cases were then carried out and the models outputs statistically evaluated. This process was repeated over a four (4) months period. Several coefficients were implemented until the researcher finally chose one which fairly represents the active system of the older person based on results from the statistical analysis. Table 5.8 shows details of the final new sets of coefficients developed for the active system of the older person and implemented in equation 5.1

Table 5.8 New Coefficients for Older Persons

	SH	CS	DL	SW
A1	6.01	4.99	13.38	0.03
A2	0.08	0.2	0.01	0.02
A3	1.18	1.41	-1.98	-1.02
A4	-1.4	-4.65	14.19	0.97
B1	0	0	17.17	2.07
B2	0	0	9.73	0.35
B3	0	0	-4.85	-6.77
B4	-23.54	0	3.02	5.68
C	1.1	2.19	0	0
D	-30.53	0	0	0

5.10 Summary of the Chapter

In this chapter, the need for an optimisation algorithms to be used for the determinations of the new sets of coefficients for the older person active system was established and the selected package and its underlining principles where reviewed. The chapter also outlined the modifications procedure adopted and established the process of optimisation. After several optimisation runs including several calculations of the RMSE for the various test experiments, and detailed analysis of the outputs generated, a new set coefficients were developed for the active system for the older person. This has resulted in the creations of new older person's active system. As it stands, this model needs to be verified and validated to see how well it predicts for the older person. Chapter 6 proceeds with the discussion of results of the verification and validation carried out.

Chapter 6

Results and Analysis

6.1 Introduction

The previous chapters described how Fiala Model was modified to reflect the body composition and control system of the older person resulting in a new Older Persons Model. The first stage involved the modification of the body composition (passive system) of the original model to reflect a typical older person. The second stage involved the modification of the active system of the model using a novel optimisation technique to arrive at new sets of coefficients for the control equations.

This chapter presents and discusses the verification and validation results of the following models:

- The new model with older person passive and active system - The Older Persons Model.
- Fiala Model with older person's body (modified passive system - typical older person).
- Fiala Model used to carry out simulation for older persons.
- Fiala Model used for the simulations involving young persons.

The Older Persons Model was tested for its predictive capabilities in terms of the thermal response of older person as compared to the other models. Fiala Model was used to predict for test cases for older persons by the setting the core temperature starting point for the simulation to that of the older person as sourced from the published experimental test cases. This was done to establish its predictive capabilities should it be used to predict for older persons in its current composition. Simulations were also carried out using the model with the modified passive system (body composition of the older person). This was to analyse the models predictive behaviour should only the passive system (body parameters) be modified without the modification of the active system. To compare the accuracy and predictive strength of the Older Persons Model to the Fiala Model, the Fiala Model was used to simulate all test cases used in the development and validation process and the results were compared with the experimental results of young subjects. Various statistical metrics were calculated to establish the accuracy of its prediction and to draw inferences from its capabilities as compared to the Older Persons Model. This was to confirm whether the new model for the older person predict as well for the older person as does the original Fiala Model for the young persons.

6.2 Verification and Validation

Verification process seeks to confirm whether the algorithms are properly implemented and errors eliminated from a designed model (Robinson, 1997, Macal, 2005). Whiles Validation is the confirmation that, the model possesses a reasonable range of accuracy for its designed purpose (Sargent, 2010). Validation ensures that the model meets its intended design requirements (Macal, 2005). It is not possible to fully verify a model (Carson, 2002), in that since models are representations of systems their behaviour is at best an approximation of that systems behaviour. In reality when a model is said to be verified and validated the understanding is that;

"Explicitly series of tasks have been carried out to verify and validate it to the degree necessary for its purposes which is always a matter of judgment" (Carson, 2002)

In this current research, validation and verification processes were carried out iteratively with occasional modification of the models underlying codes when the need arise. The data used in the design of the model (calibration) was used for verification whiles collated data, independent of the one used in the model development was used for validation. Results from the models were compared with the experimental measurements for both verification and validation processes. At any point in the process where there exist wide discrepancies between the predicted values and the measured experimental results the process reverts to the calibration point. Agreement between the predicted values and the measured experimental values were evaluated using statistical matrices (section 6.3).

At the developmental stage of a model, the specific purpose of the model is defined and its validity determined with respect to that purpose (Sargent, 2010). Therefore in undertaking model verification and validation, the current research seeks to evaluate the models predictive capabilities first (verification) for predictions in the region of experiments used in its development then second (in validation), for predictions in the untested regions of applications (independent data sets not used in the model modification process). The current Older Persons Model focused on the core temperature and mean skin temperature prediction of the older person. More attention was however deliberately focused on the core body temperature due to its importance in the analysis of the physiological and thermal state of the human body. As a result the statistical analysis were carried out for the models core body and the mean skin temperature results in comparison with the experimental measurements of skin and core temperature for older subjects.

6.3 Statistical Metrics – Goodness of Fit

In relation to this work, the author used seven (7) statistical metrics including; the residual sum of squares (RSS), Root mean square error (RMSE), weighted average of the RMSE, the maximum residual - $e$max, the minimum residual - $e$min, the mean absolute difference (MAD), the coefficient of determination and the 95 percentile in analysing the results of the models in relation to experimental data set. The residual sum of squares (RSS) or sometimes referred to as the sum of the squared errors of prediction (SSE or SS_{er}) is the difference between the observed value ***(y_i)*** and the associated predicted value of the model **(f_i)**. The formula for the residuals is given as:

$$e_i = (y_i - f_i) \tag{6.1}$$

The formula for the sum of squared errors of prediction is given as:

$$SS_{er} = \sum_{i=1}^{n} (y_i - f_i)^2 \tag{6.2}$$

Where n is the number of observations. A smaller value of the sum of squared errors of prediction indicates that the predictions of the models are closer to the observed data. The root mean square error (RMSE) is a measure of how close a fitted line is to data points. In terms of evaluating the goodness of fit of models, for the same experimental test setting RMSE is used to measure the difference between the results of a model and the measured experimental data. Its formula is given as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - f_i)^2}{n}} \tag{6.3}$$

The weighted average takes into consideration the proportional relevance of each test case in the data set including number of subjects in each test rather than treating the entire test as having equal composition. In this case, the calculated weighted average results from the weighting of the RMSE of each test with the number of subjects and total number of subjects given as:

$$Weighted\ Average = \frac{\sum_{i=1}^{n} RMSE_i * N_i}{\sum_{i=1}^{n} N_i} \tag{6.4}$$

Where N is the total number of subjects in each experiment

Coefficient of determination denoted as $\boldsymbol{R^2}$ is another parameter which is used to determine the goodness of fit of a model. The $\boldsymbol{R^2}$ is often evaluated as a number between 0 and 1.0 and the higher this value is or closer to 1.0 gives an indication of how close the models predictions are to the observed data. The formula for $\boldsymbol{R^2}$ is given as:

$$\boldsymbol{R^2} = 1 - \frac{SS_{er}}{SS_{tot}} \tag{6.5}$$

Where $\boldsymbol{SS_{tot}}$ is the total sum of squares given as:

$$SS_{tot} = \sum_{i=1}^{n}(y_i - \bar{y}_i)^2 \tag{6.6}$$

Where $\bar{y}$ is the mean of the observed values given as:

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{6.7}$$

The Maximum residual ($e$max) and the minimum residual ($e$min) are usually useful in analysing the range of differences in the residuals. But to be able to show the overall magnitude of the differences, mean absolute difference gives a clearer value for such analysis. The equation for the mean absolute difference is given as:

$$Mean\ Absolute\ Difference = \frac{1}{n}\sum_{i=1}^{n} |e_i| \tag{6.8}$$

Where $|e_i|$ is the values of the absolute residual

6.4 Body Core Temperature

This section reports results of calculated statistical metrics of the various models for the core body temperature. The core body temperature is the temperature of the deep structures of the body including the brain and organs within the thoracic and abdominal cavities and has an optimal value of 37°C. It can be measured with thermometer placed in the rectum, mouth, esophageal, the ear, under the armpit and urine. Each of these mediums gives a representative value of the body temperature but variations exits between sites (Chapter 3). In most of the test cases, the core body temperature was measured from the rectum as a result the models rectal results were used for the analysis. However test cases (26, 28 & 40°C) used esophageal measurement for core body temperature but their results were also compared with the rectal results of the model.

6.4.1 Verification

Figure 6.1 to Figure 6.8 shows the results of the all the test cases (5, 12, 17, 21, 26.5, 28, 30, 42) °C which were used in the calibrations of the Older Persons Model. Results of the Fiala model used for the younger subject's predictions compared with the experimental results of younger subjects are shown in Appendix E. In all, eight (8) test cases involving 109 subjects both men and women took part in the older person's experiments. It can be seen in Figure 6.1 that, the prediction of the Older Persons Model follows the trend of the experimental results of older persons. The models results were in good agreement at the beginning of the exposure and followed the same pattern when the subjects engaged in exercise (4.0 met) at 30 minutes into the experiment. At 50 minutes into the test, the prediction of the model showed signs of deviation from the experimental results and this trend continued until the end of the test (60 minutes). Whilst the experimental results pointed to a downward trend, that of the model show an upward trend, resulting in an end of test minimal deviation of 0.3°C from the experimental results.

However, when the Fiala Model was used for older person's predictions, the models results deviated from the experimental results from the start of the experiment even though the predictions follow the trend of the experiments. At the start of the exposure to 5°C, Fiala Models prediction was 0.13°C higher than the experimental results. This trend continued over the test period resulting in an end of test core temperature reading of 37.2°C which was 0.8°C higher than the experimental value. When the Fiala Model with older person's body was used for older person's predictions, at the start of the 5°C exposure a 0.17°C difference in temperature compared with experimental results was recorded. The prediction (Figure 6.1) did not follow the trend of the experiments but rather show an upward trend which continued throughout the test period. This upward trend became more pronounced when test subjects engaged in an exercise 30 minutes into the 5°C experiment. At the end of the experiment, the model's prediction recorded a high temperature difference of 1.06°C in comparison with the experimental results.   In this validations experiment, the Older Persons Model appears to be the best predictor of the core body temperature.

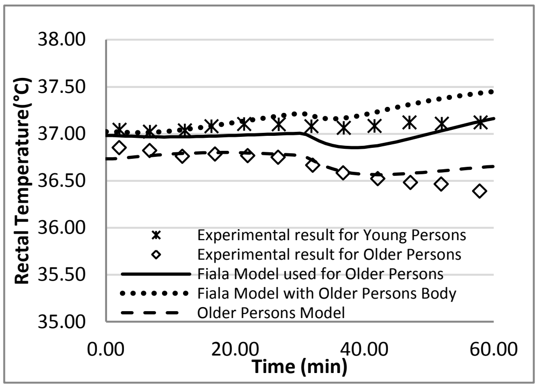

Figure 6.1 Experimental exposure of 5°C

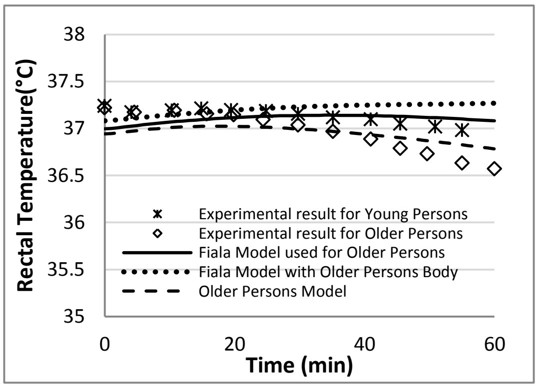

Figure 6.2 Experimental exposure of 12°C

It can be seen from Figure 6.2 that, the Older Persons Model recorded a lower core temperature of 36.94°C as against 37.22°C for the experimental result at the start of the experiment. This trend continued until 20 minutes into the test where the results of the model show good agreement with experimental results. At 50 minutes, the models prediction deviated from the experimental results thereby recording an end of test core body temperature of 36.78°C as against 36.57°C for the experimental result. Results of Fiala Model used for older persons show that, at the start of the 12°C exposure, the core body temperature was 0.22°C lower compared to the experimental measurement (37.22°C). This continued up to 10 minutes into the test before the model's result shows agreement with experimental results. This was the case up to 30 minutes when the experimental results show a downward trend but the model did not respond to the fall in core temperature. At the end of the test, measured experimental core temperature was 36.57°C as against 37.08°C for the model which shows quite a high difference implying an overestimation of the core temperature by the model in this test case.

Additionally, Fiala Model with older person's body was also used to simulate the test conditions of 12°C and results for the simulation (Figure 6.2) show a lower core temperature prediction of the model (0.14°C) at the beginning of the test compared with measured experimental results. However, after 5 minutes into the experiment, the models prediction shows good agreement with experimental result until 30 minutes when the predictions show an upward deviation in contrast to the experimental results which points to a fall in core body temperature. This led to an end of test core temperature value of 37.27°C for the model as compared to 36.57°C for the experimental result. Results in Figure 6.2 show that, the Older Person Model did not entirely agree with the experimental results but reasonably follows the trend of the measured results.

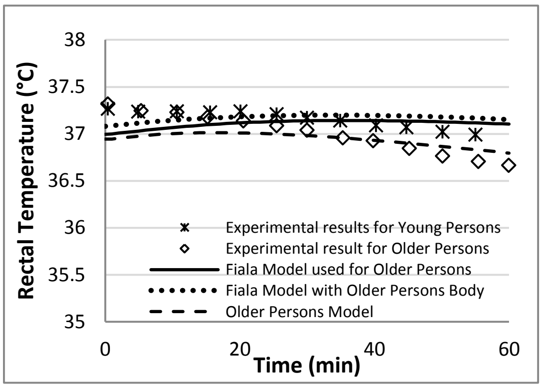

Figure 6.3 Experimental exposure of 17°C

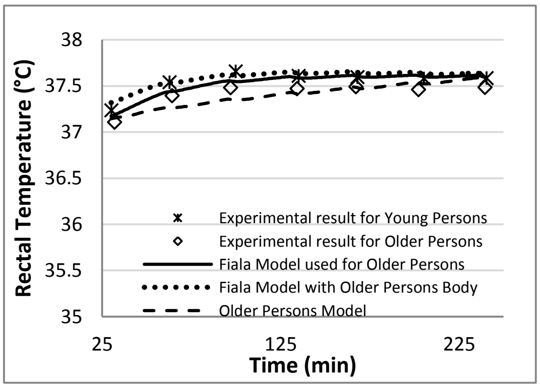

Figure 6.4 Experimental exposure of 21°C

From Figure 6.3 the Older Persons Model recorded a lower core temperature of 36.94°C as against 37.32°C for the experimental result. This was the trend until 25 minutes into the test where the models result shows good agreement with experimental results up to 55 minutes. From this time, the models prediction deviated slightly from the experimental results recording an end of test core body temperature of 36.80°C as against 36.66°C for the experimental measurement.

Results of Fiala Model used for older persons show that, at the start of the 17°C exposure, the core body temperature was lower (0.32°C) as compared to the experimental result. This trend continued up to 15 minutes into the test before the models prediction shows agreement with experimental measurement for the next 15 minutes. Thereafter the models results deviated with a slight upward trend whiles the experimental results show a downward trend. This was the trend until the end of the test with measured experimental core temperature at 37.10°C as against 36.66°C. Fiala Model with older person's body results (Figure 6.3) show that, at the beginning of the test, core temperature prediction of the model was 0.24°C lower than the measured experimental result. However, after 5 minutes into the experiment, the models prediction shows good agreement with experimental data until 30 minutes when the predictions begun an upward deviation whilst the experimental results points to a fall in core temperature. This led to an end of test core temperature value of 37.15°C for the model as compared to 36.66°C for the experimental result. Results (Figure 6.3) show that the Older Persons Model in this test experiment (17°C) agreed with the experimental results with some deviations but reasonably follows the trend of the results.

It can be seen from Figure 6.4 that, the Older Persons model results show reasonable agreement with measured experimental values. Whiles at the start of the measurement it agreed well with the experimental measurement, its trend of prediction varied minimally but still followed precisely that of the experimental measurement. The difference in the models prediction and measured values were not statistically significant. Fiala Model used for older person's results agreed well with experimental measurement from the start of the measurement until the end of the test. Furthermore, Fiala Model with older person's body results agreed well with the trend of experimental data but recorded some deviations at the start of the measurement. But these deviations were not statistically significant. Results in Figure 6.4 show that in this test condition of temperature 21°C with 80% relative humidity, all the models show reasonable agreement with experimental results.

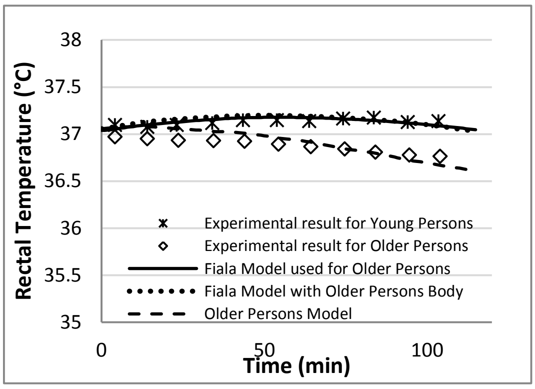

Figure 6.5 Experimental exposure of 26.5°C

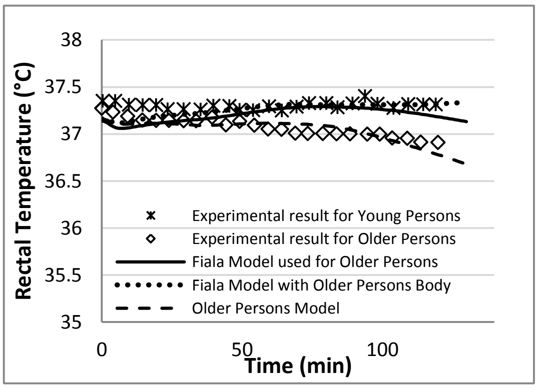

Figure 6.6 Experimental exposure of 28°C

Figure 6.5 shows the Older Persons models prediction which was in good agreement with experimental results from the beginning of the test until the end. However, for Fiala Model used for older person's prediction, the result did not agree with experimental results of older persons but surprisingly rather agreed with that of the young person. This was the same for the Fiala Model with older person's body. The recorded end of test body core temperature was 37.0°C for both Fiala Model with older person's body and Fiala Model used for older persons as against 36.7°C for the experimental result for older persons. The Older Persons Model in this test case displayed good predictive capability whereas the other models appear to have overestimated the core body temperature.

Figure 6.6 shows the results of experimental exposure of 28°C. It can be seen that, Fiala Model used for older person's results show good agreement with experimental results at the start of the test up to 50 minutes into the test. At this point the models results deviated upwards whilst the experimental result for the older person's shows a downward trend. The models prediction rather agreed with the measured data of young test subjects from 50 minutes onwards until the end of the test. This was the same for the Fiala Model with older person's body. The recorded end of test body core temperature was 37.1°C as against 36.9°C for measured experimental value for older persons. From Figure 6.6 the Older Persons models prediction displayed good agreement with experimental results from the beginning of the test until the end highlighting the models predictive capability.

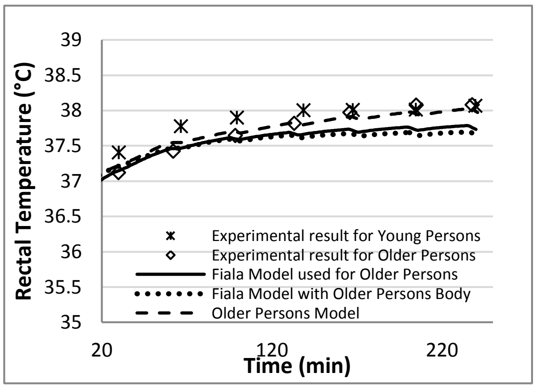

Figure 6.7 Experimental exposure of 30°C

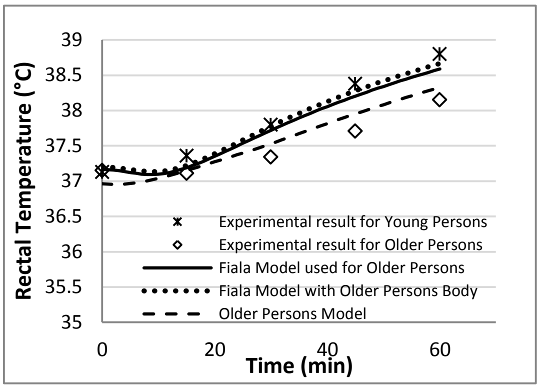

Figure 6.8 Experimental exposure of 42°C

Figure 6.7 shows the results of 30°C exposure in which the prediction of Fiala Model with older person's body agreed well with experimental results from the beginning of the experiment but deviated after 120 minutes. This trend continued till the end of the test (220 min) with a recorded core body temperature of 37.5°C as against 38.0°C for the measured experimental value. However the Older Persons Model prediction from the beginning of the measurement until the end of the test shows good agreement with the experimental results. Results of Fiala model used for the older persons agreed with experimental measurements up to 120 minutes before deviating. End of test core body temperature predictions of the model was 37.5°C with the measured value being 38.0°C.

In the experimental exposure of 42°C (Figure 6.8), it can be observed that the Older Persons Models prediction shows reasonable agreement with experimental results and follows the trend with some minimal deviations which were not statistically significant. However results of Fiala Model used for older persons did not agree with experimental measurement but rather show agreement with the young person measurement. This was the same for Fiala Model with older person's body. The recorded end of test body core temperature was 38.5°C for both Fiala Model with older persons body and Fiala Model used for older person as against 38.1°C for measured experimental value for older persons. All the results point to a strong predictive capability of the Older Persons Model.

Figure 6.9 shows the Root Mean Square Error (RMSE) values for test cases used in the calibration of the model. For the Older Persons Model, out of eight (8) test cases, five (5, 21, 26.5, 28, 30) °C had RMSE of the core temperature prediction below 0.1.

Two test cases (12, 17) °C recorded RMSE below 0.2 with one test which had a RMSE above 0.4 (42°C). These results show good agreement of the models results with measured data. However for Fiala Model with older person's body, the results were quite erratic with test cases (5, 12 and 42) °C recording RMSE values above 0.3 and test case 5°C recording the highest of 0.69 RMSE. Five other test cases (17, 21, 26.5, 28, and 30) °C all had RMSE's above 0.2. None of the RMSE values for Fiala Model with older person's body were below that of the Older Person's Model. These results highlight possibly the better predictive capability of the Older Persons Model in realistically predicting the body core temperature which is a vital body parameter in the determination of the thermal state of a person. Fiala Model used for older persons had RMSE values which were all above 0.2 except for test conditions 21°C and 30°C where the RMSE's were below 0.2. In all the verification test cases none of the RMSE's for the Fiala Model used for older persons were lower than that of the Older Persons model.

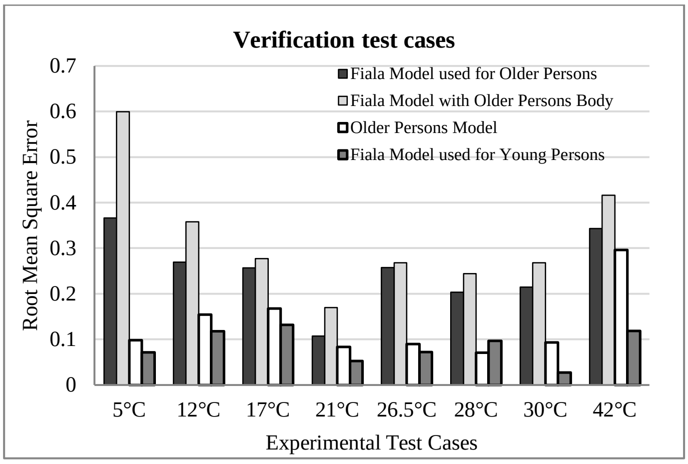

Figure 6.9 Root mean Square Error for Verification test cases

In a comparative analysis in the context of their respective fields of application, i.e. Fiala Model used in predictions for the young the RMSE's results show a strong predictive capability. But as seen from the RMSE results the same cannot be said when it is used for the prediction for the older person or if only the passive system was modified. From Figure 6.9, it can be observed that, Fiala model as expected displays strong predictive capability in all of the eight test cases for younger subjects. Five (5) test cases (5, 21, 26, 28, and 30) °C all had their RMSE well below 0.1 with three test cases (12, 17, and 42) °C with RMSE just above 0.1. The only model demonstrating close correlative resemblance to the predictive capabilities of the original Fiala model is the Older Persons Model. In order to further evaluate the predictive capabilities of these models, the weighted average (WA) of the RMSE was calculated using equation 6.4 for all test cases for each model. In Figure 6.10, the Older Persons Model appears to have a strong predictive capability in relation to core temperature predictions.

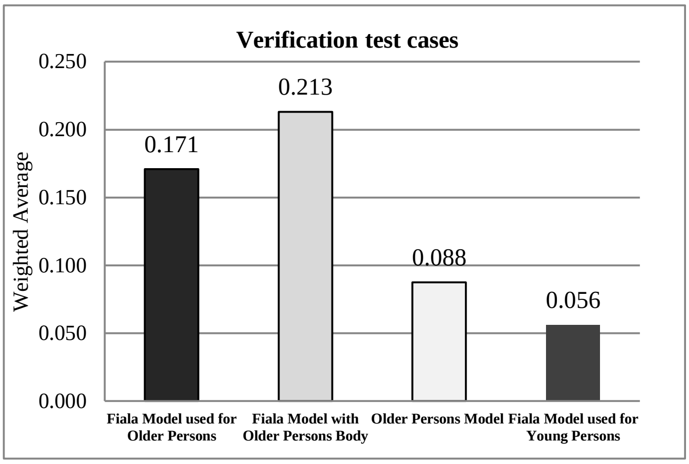

Figure 6.10 Weighted Average for Verification test cases

However the results of the Fiala Model with older persons body show that, modifying the passive system alone may have compromised the core temperature behaviour of the model and this strongly underlines the need to further develop that active system. Using the Fiala Model in its current form and composition for the prediction of the core temperature behaviour of older people also reflects the need to carry out modification in order to adapt it to the needs of the older population. In the comparative analysis in the context of their respective fields of application, Fiala Models calculated weighted average value of 0.056 reflected its strong predictive capabilities and the Older Persons Model weighted average value of 0.088 demonstrated a close resemblance to the predictive capabilities of the original Fiala model.

6.4.2 Validation

Figure 6.11 to figure 6.14 show the results of the entire test cases (8, 12, 40, and 41) °C used in validating the model. Results of the Fiala model used for the younger subject’s predictions compared with the experimental results of younger subjects are shown in Appendix E. In all, 46 test subjects both men and women took part in the experiments for the older persons. Figure 6.11 shows that, the prediction of Fiala Model used for older person agreed with older person's experimental results from the start of the experiment up to 50 minutes. At this point when the measured data points to a fall in core temperature the models results appear to be constant at 37.4°C. This trend continued until the end of the test with the models predictions recording a core temperature of 37.4°C as against 37.0°C for the measured data. However, results of the Older Persons Model agreed well with measured data and followed the trend of the data set. Furthermore, results of Fiala model with older person's body agreed with older person's experimental results from the start of the experiment up to 50 minutes before deviating recording an end of test core temperature value of 37.45°C against 37.0°C for the measured data. In this first validation case, the Older Persons Model shows good predictive capabilities as against the other models.

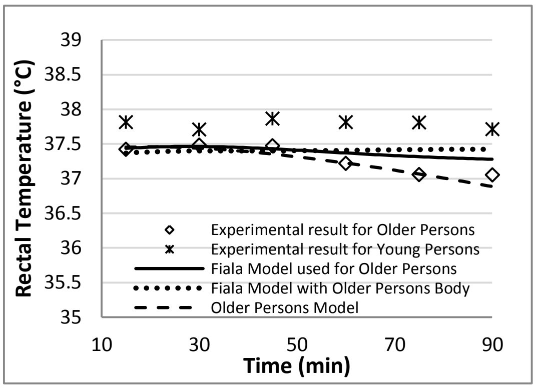

Figure 6.11 Experimental exposure of 8°C

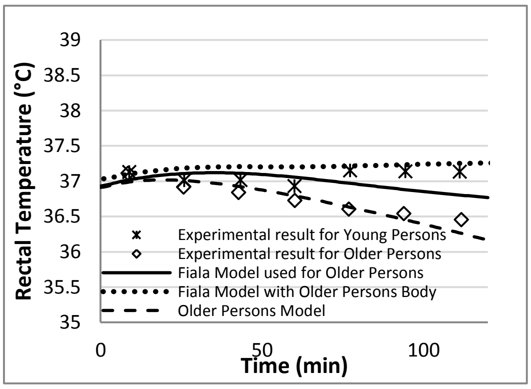

Figure 6.12 Experimental exposure of 12°C

Figure 6.12 show the results of 12°C experimental exposure, For Fiala Model used for older person its predictions did not agree with older persons measured data. From 20 minutes into the experiment deviations were evident in the models prediction compared to experimental results and this continued till the end of the test. The end of test core temperature value for the model stood at 37.36.8°C as against 36.5°C for measured data. However the Older Persons Model predictions agreed well with measured data and followed the trend of the experimental results from the beginning of the test until the end. Results of Fiala model with older person's body also did not agree with older persons measured data from the start of the experiment up to the end of the test. The models predictions were rather in agreement with the younger persons measured data which shows that the model in this case overestimated the core temperature of the older person. Results of this test case confirm that the Older Persons Model prediction better reflects the thermal responses of the older persons.

Figure 6.13 shows that results of experimental exposure of 40°C where measured data for the core body temperature was taken from the esophageal. Results of Fiala Model used for older person did not agree with older person's experimental results from the beginning of the test but 50 minutes into the test, the results show good agreement. This trend continued until the end of the test. However the predicted values of Older Person Model agreed with measured data over the duration of the exposure. In relation to Fiala model with older person's body the results show the same predictions pattern of Fiala Model used for older person.

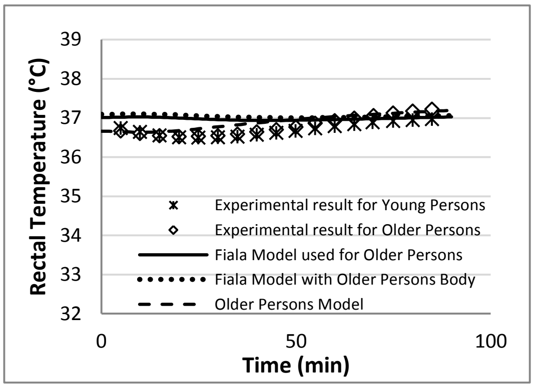

Figure 6.13 Experimental exposure of 40°C

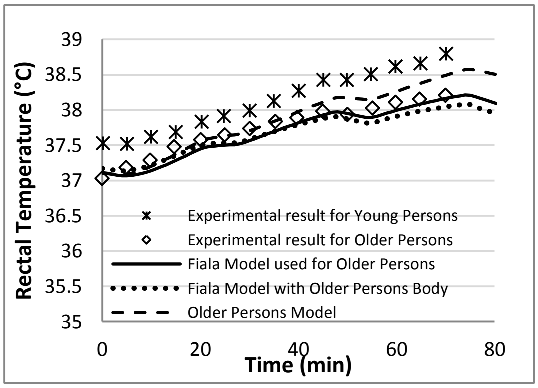

Figure 6.14 Experimental exposure of 41°C

From Figure 6.14, the predictions of Fiala Model used for older person agreed well with older persons measured data over the test period. The Older Persons Model results also agreed with experimental results over the duration of the exposure but the last 10 minutes witnessed minimal deviations leading to an end of test core temperature reading of 38.5°C as against measured data of 38.1°C. For the Fiala model with older person's body, the results show the same prediction pattern of Fiala Model used for older person. Figure 6.15 show the Root Mean Square Error (RMSE) plots for the test cases used in validating the model. From Figure 6.15 it can be observed that the RMSE for Older Persons Model for all the test cases fell below 0.15 where test case 8°C had a RMSE of 0.08 reflecting a good agreement with experimental data. Fiala Model with older person's body had three of the test cases which were above 0.3 with only one test case (41°C) recording a RMSE of 0.14. It was also observed that in comparison with the Older Persons Model none of the RMSE values for Fiala Model with older person's body was below that of the Older Persons Model. This trend highlights the predictive capabilities of the Older Persons Model over the exposures analysed.

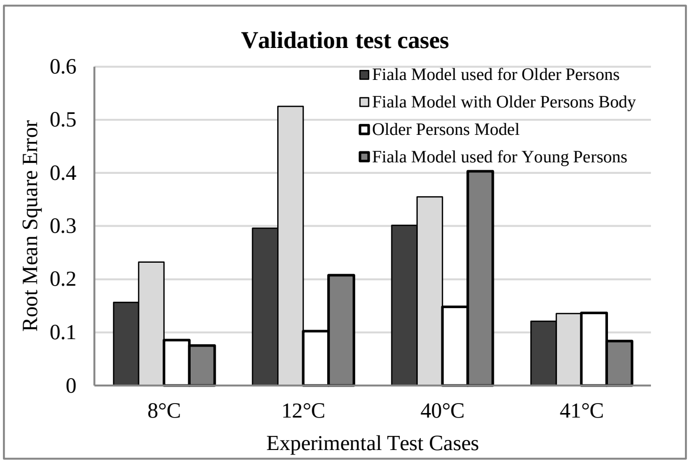

Figure 6.15 Root mean square Error for Validation test cases

RMSE for Fiala Model used for older persons was 0.3 for two test cases (12 and 40) °C; two others (8, 41°C) had RMSE of 0.16 and 0.12 respectively. In all the validation test cases only one of the test cases (41°C) had RMSE's lower than that of the Older Persons Model highlighting the ability of the current older person's model to predict better than the original Fiala Model when used for older person prediction. In a comparative analysis in the context of their respective fields of application, Fiala model used for young person's result shows varied RMSE's with 0.4 for test case 40°C, 0.21 for 12°C and RMSE below 0.1 for test cases (8, 41°C). In order to further evaluate the predictive capabilities of these models, the weighted average of the RMSE was calculated using equation 6.4 for all test cases for each model. From Figure 6.16 it can be observed that the Older Persons Model appears to have a strong predictive capability with a calculated weighted average value of 0.025.

However the results of the Fiala Model with older person's body reveals the highest (0.060) followed by Fiala Model used for older person's prediction. A look at the results indicates that, the modification of the passive system did not enhance the predictive capability of the model. Furthermore using the model in its current form for older person's prediction may not in majority of cases produce accurate results.

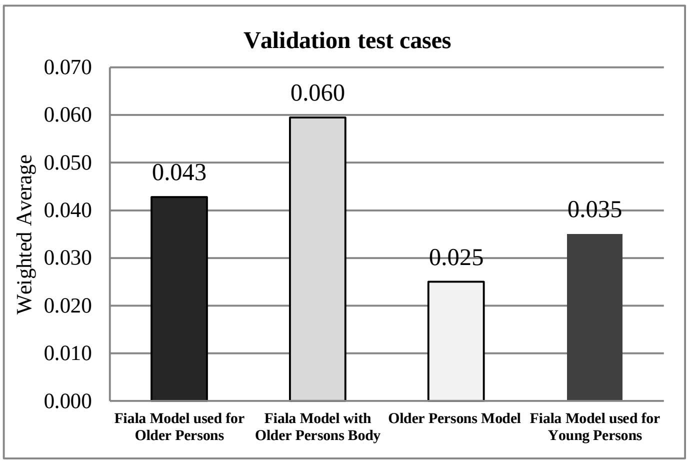

Figure 6.16 Weighted Average for Validation test cases

In the comparative analysis in the context of their respective fields of application, Fiala Models calculated weighted average value of 0.035 reflected its strong predictive abilities for young persons and the Older Persons Model weighted average value of 0.025 for older persons.

6.4.3 Overall Body Core Temperature Statistical Evaluation

Figure 6.17 shows the average values of the RMSE for the entire data sets used in the core temperature calibration and validation. As has been reported in the various test cases, the Older Persons Model shows reasonably strong predictive capability compared to the other models analysed. In a comparative analysis carried out on the model in the context of their respective fields of application, i.e. Fiala Model used in predictions for the young and the Older Persons Model used for the predictions of the Older person, the RMSE's was 0.12 and 0.13 respectively. This close resemblance in their statistical metrics underlines the strong correlation between the predictive capabilities of these models. Revealing that, for body core temperature predictions the Older Persons Model predicts well for the older person as does the original Fiala Model for the younger persons.

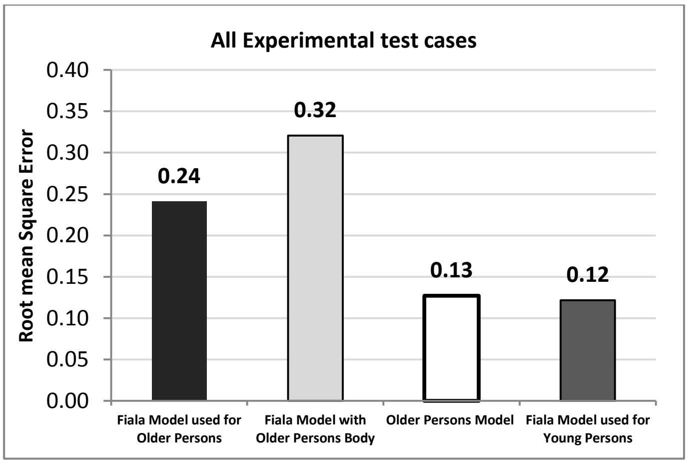

Figure 6.17 Root mean Square Error for all test cases

The same correlative trend can be observed in the calculated values for the weighted average of the RMSE, (Figure 6.18) where the Older Persons Model also showed a strong predictive capability in comparison with the predictive capabilities of the original Fiala Model.

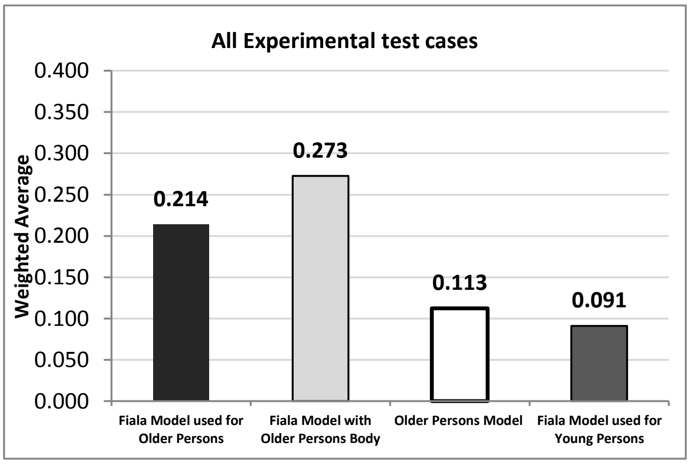

Figure 6.18 Weighted Average for all test cases

Table 6.1 shows the list of other statistical values calculated from the predictions of the models (Older Persons Model, Fiala Model with older person's body, Fiala Model used for older persons, Fiala Model used for younger persons). These include the maximum residual errors (*e*max) and minimum residual errors (*e*min), the mean average deviation (MAD), the coefficient of determination and the 95 percentile.

Table 6.1Comparison of statistical Metrics for core body temperature

Statistical Evaluation Table - Body Core Temperature (T_{re})				
	Fiala Model used for Older Persons	**Fiala Model with Older Persons Body**	**Older Persons Model**	**Fiala Model used for Young Persons**
Root Mean Square Error	0.24	0.32	0.13	0.12
Weighted Average	0.214	0.273	0.113	0.091
emax	0.35	0.43	0.37	0.24
emin	-0.74	-1.05	-0.41	-0.59
Mean Average Deviation	0.21	0.27	0.10	0.12
R^2	0.63	0.33	0.90	0.87
95 percentile	0.47	0.64	0.25	0.42

The Fiala Model with older person’s body has the lowest coefficient of determination (0.33) and the highest mean average deviation (0.27) when compared to other models. This reveals that, the predicted values calculated by the model are furthest from the observed data. Furthermore, from Table 6.1, Fiala Model used for older person’s prediction had a coefficient of determination (0.63) and a mean absolute deviation of 0.21. These results show that, the predicted values of the model are also far from the observed data but not as much as Fiala Model with older person’s body.

However, significant improvements in predicting the core temperature of the older person were recorded by the Older Persons Model with the coefficient of determination (0.90) and the lowest mean absolute deviation (0.10). These results show that the predicted values of the Older Persons Model are closest to the measured core body temperature in all the experiments used. In a comparative analysis in the context of their prediction for core temperature in their respective fields of application, Fiala Model has coefficient of determination (0.87) and mean average deviation of (0.12) showing that, the predicted values calculated by the model are close to the measured experimental data of young subjects. Comparatively the Older Persons Model calculated values (coefficient of determination (0.90) and mean average deviation (0.10)) reflects the correlation between the predictive capabilities of these models in their individual fields.

Table 6.1 also shows the results of the maximum residual (*e*max) and minimum residual (*e*min) of the models with the Fiala Model with older person’s body recording the widest range of residuals (0.45 to -1.05). However, Fiala Model used for older person’s prediction has (0.35 to – 0.74) with Older Persons Model recording the narrowest range of residuals (0.37 to -0.41). The calculated 95 percentile values indicate that the Older Persons Model value of 0.25 reflects a better distribution of its results compared to other models (Fiala Model with older person's body (0.64) and Fiala Model used for older person's prediction (0.47)).

6.5 Summary for Body Core Temperature

The core temperature predictions for the Older Persons Model are far better than that of the Fiala Model used for older person's predictions and the Fiala Model with older person's body composition. The statistical metrics indicate that the predictions of Fiala Model with older person's body composition for the core body temperature were worse than that of the original Fiala Model. Older Persons Model appears to be the best predictor of the core temperature for the older person.

6.6 Mean Skin Temperature

In this section, analysis of the results of calculated statistical metrics of the various models was undertaken for the mean skin temperature. Mean skin temperature reflects human response to thermal stimulus and states of heat exchange between the human body and the thermal environment (Liu et al., 2011). Due to local temperature variations in the skin (Vanos et al., 2010) its measurement is a difficult process. Many formula(s) (Chapter 2) have been developed to assist in arriving at the best possible value for the mean skin temperature. There is therefore no one acceptable formula for calculating the mean skin temperature. Investigators therefore in the design of their experiments select the one they believe would produce the best value for mean skin temperature. This therefore introduces complications in the event that; when several test cases are brought together for modelling purposes, the use of varying formulas could induce embedded variations which may affect the outcome of the models predictions.

In fact the best scenarios would be the collations of experiments with the same formulas in order to eliminate these complexities. But since experimental test case for older persons were hard to come by, this research combined several test cases with different formula(s) for mean skin temperature calculation. In fact, in some cases the formula used were not reported.

6.6.1 Verification

Figure 6.19 to Figure 6.22 show the experimental results of the all the test cases (12, 17, 26, and 28) °C which were used in the calibrations of the model. In all, 72 test subjects both men and women took part. Results of the Fiala model used for the younger subject's predictions compared with the experimental results of younger subjects are shown in Appendix E. Figure 6.19 shows that the predictions of the Older Persons Model follow the trend of the experimental results of the older persons however; there were deviations over the duration of the test. This was the case for Fiala Model with older person's body and Fiala Model used for older persons. Figure 6.20 shows the results of experimental exposure of 17°C and also reveal the same pattern as in Figure 6.19. It was evident in these cases that, even though the predictions of the models did reasonably follow the trend of the measured data, agreement with experimental results were limited. In this case the models slightly overestimated the values for the mean skin temperature. The same trend occurs in environmental exposures of 26°C (Figure 6.21) and 28°C (Figure 6.22).

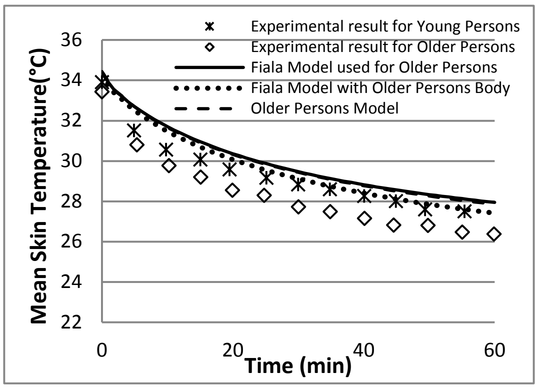

Figure 6.19 Experimental exposure of 12°C

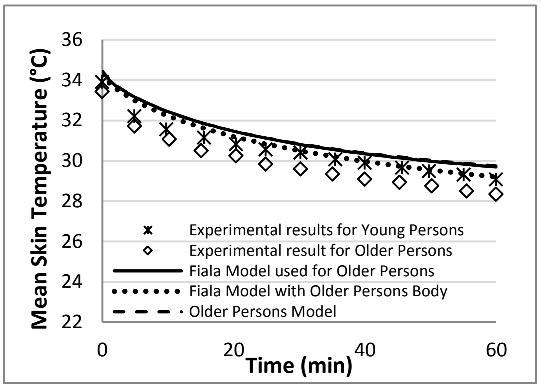

Figure 6.20 Experimental exposure of 17°C

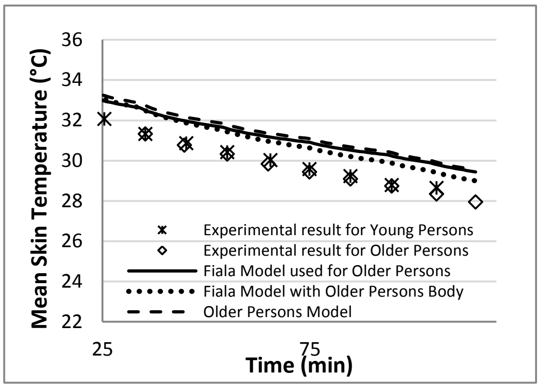

Figure 6.21 Experimental exposure of 26°C

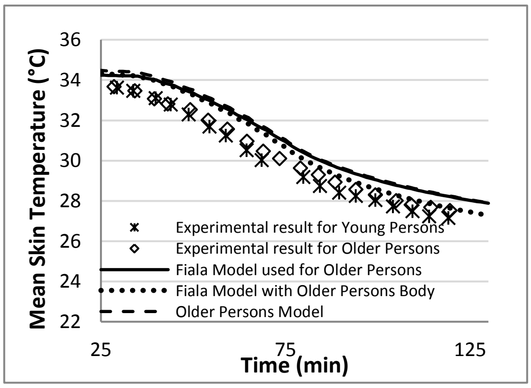

Figure 6.22 Experimental exposure of 28°C

Figure 6.23 shows the Root means square error (RMSE) for the test cases used in the calibration of the model. It can be seen that, the Older Persons Model show quite an erratic format of RMSE result with only one test case (28°C) out of the four test cases which had a RMSE of 1.0. However the other three test cases (12, 17, 26°C) had RMSE more than 1.0. Test case 12°C and 26°C had RMSE of 1.6 each whilst test case 17°C had a RMSE of 2.9. This RMSE values were quite high reflecting some limitations with the Older Person's Model mean skin temperature results. Fiala Model used for older persons predictions had a RMSE of 0.7 for test case (28°C) which was lower than that of the Older Person's Model and in other test cases (12, 17, 26°C), RMSE's were found to be lower than that of the Older Persons Model. A similar trend can be observed in the case of Fiala Model with older person's body. Fiala Model used for younger person's prediction was the lowest in all test cases except test case 28°C.

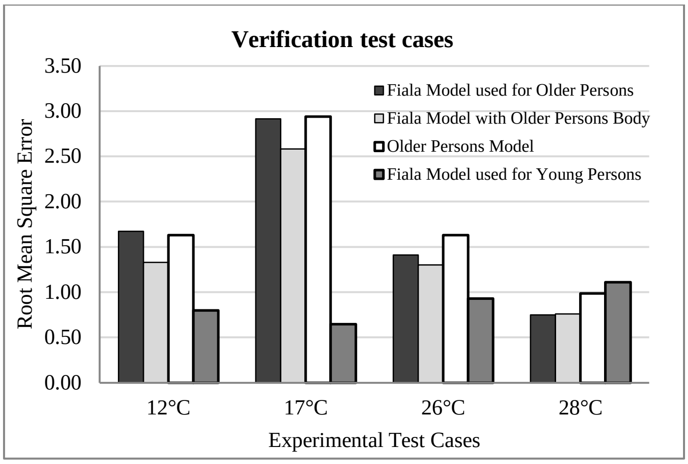

Figure 6.23 RMSE for Verification test cases

Fiala Model's RMSE for test case (28°C) show a rather high RMSE of 1.1 which highlights some possible limitations of the original Fiala model when it comes to mean skin predictions. But in all other cases, it displayed good predictive capability for the young person compared to Fiala Model used for older person's predictions and the Older Persons Model. Figure 6.24 illustrates the weighted average of the calculated RMSE. This was calculated using equation 6.4. From Figure 6.24 it can be observed that the Older Persons Model appears to have recorded high values as seen from the RMSE of the individual cases.

On the other hand, results of the Fiala Model with older person's body show that, modification of the passive system did compromise the mean skin temperature behaviour of the model but not as much as that of the Fiala Model with older person's body and Older Persons Model. Fiala Model used for younger person's prediction however had the lowest weighted average value of 0.43, reflecting its strong predictive capabilities for the young person. These results show that, whiles the Older Persons Model predictions for the core temperature were in very good agreement with measured data, that of the mean skin temperature shows some limitations. Section 6.8 discuses some of the issues which may have contributed to such an occurrence.

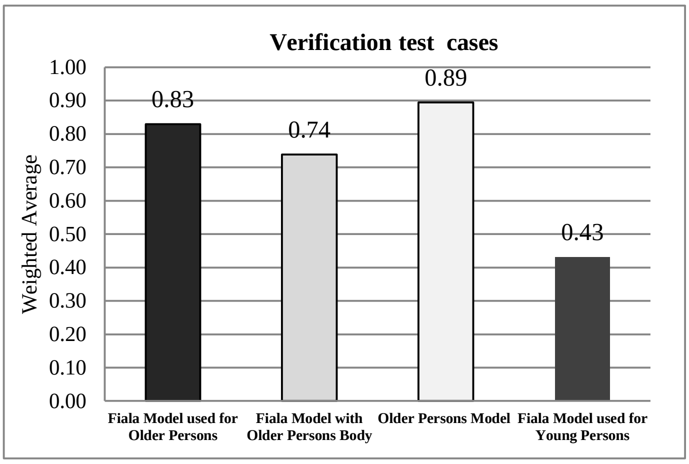

Figure 6.24 Weighted Average for verification test cases

6.6.2 Validation

Figure 6.25 to Figure 6.27 show the plots of the all the test cases (10, 40, and 41) °C which were used in the validation of the model. Results of the Fiala model used for the younger subject's predictions compared with the experimental results of younger subjects are shown in Appendix E. In all, 23 test subjects male and female were involved in the experiments for the older persons. Figure 6.25 shows that the predictions of the Older Persons Model follow the trend of the experimental results of the older persons however, over the course of the test, it did not agree with the experimental measurement. At 60 minutes into the test where the older people terminated their participation in the experiment, the measured mean skin temperature was 23.5°C but the model predicted 24.7°C. This same trend was evident in the case of Fiala Model with older person's body and Fiala Model used for older persons.

All the models had similar predictions with Fiala Model used for older person's predicting close to the young person's measured values. What is evident in this case is that, as seen in the verification cases the models slightly overestimated the values for the mean skin temperature. Figure 6.26 shows the results of experimental results of 30°C with the Older Persons Model results fairly agreeing with the measured data from the start of the experiment up to 30 minutes. After that, the models predictions deviated from the trend of the measured results with an end of test mean skin temperature of 36.0°C as against measured data of 36.9°C. This trend was also evident in the case of Fiala Model with older person's body and Fiala Model used for older persons predictions. In this case, the models slightly underestimated the values for the mean skin temperature for heat exposure of 40°C with 40% relative humidity.

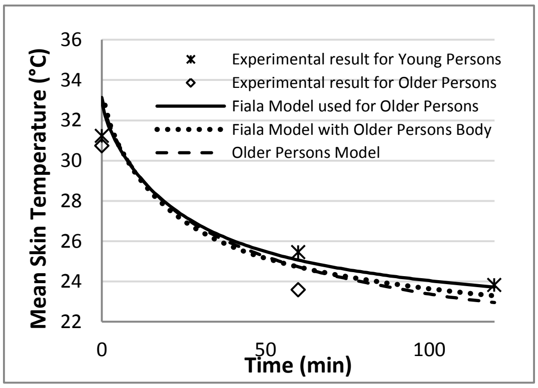

Figure 6.25 Experimental exposure of 10°C

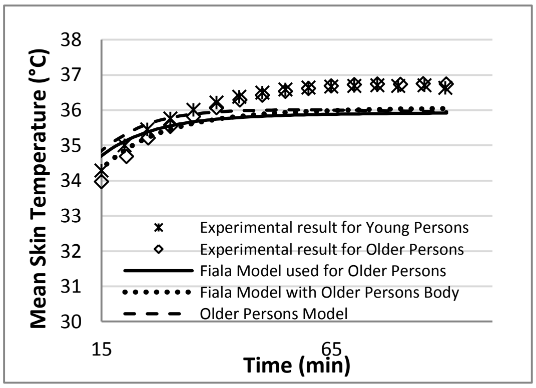

Figure 6.26 Experimental exposure of 40°C

Figure 6.27 shows the results of experimental exposure of 41°C. The Older Persons Model predictions were not in good agreement with measured data from the start of the experiment until the end. It also did not precisely follow the trend of the results and had an end of test mean skin temperature value of 36.0°C as against measured value of 38.0°C, a difference of 2°C. A similar pattern was recorded in the predictions of Fiala Model with older person's body and Fiala Model used for older persons with end of test predicted mean skin temperature of 35.0°C for both models. In this current test case (dry heat exposure of 41.5°C with 21% relative humidity) the models also underestimated the values for the mean skin temperature as in exposure of 40°C (Figure 6.26).

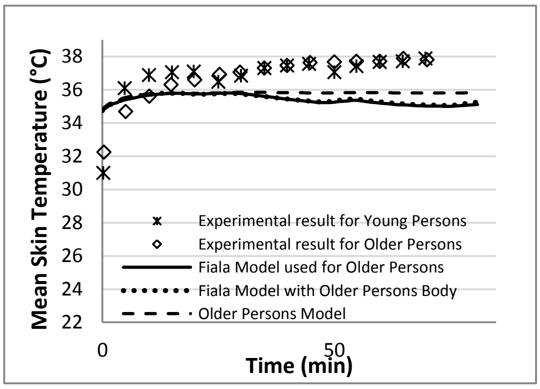

Figure 6.27 Experimental exposure of 41°C

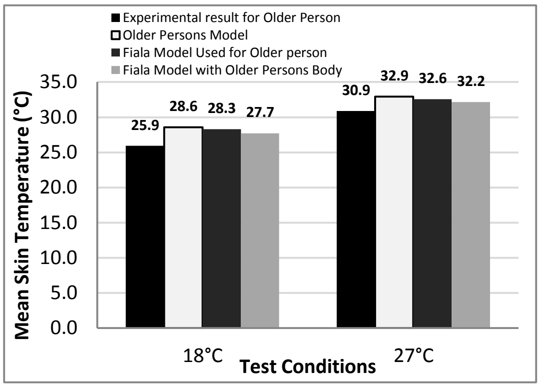

Figure 6.28 Experimental exposure of 18°C & 27°C

Figure 6.28 show the end of test results of experimental exposure of 18°C and 27°C. For the exposure to cold of 18°C with 45% relative humidity, the Older Persons Model predictions revealed an overestimation of the mean skin temperature. This was the same for the exposure to 27°C with 45% relative humidity. A similar pattern was reported in the predictions of Fiala Model with older person's body and Fiala Model used for older persons predictions. Possible issues which may have contributed to the occurrence of this variation in predictions are discussed in Section 6.8.

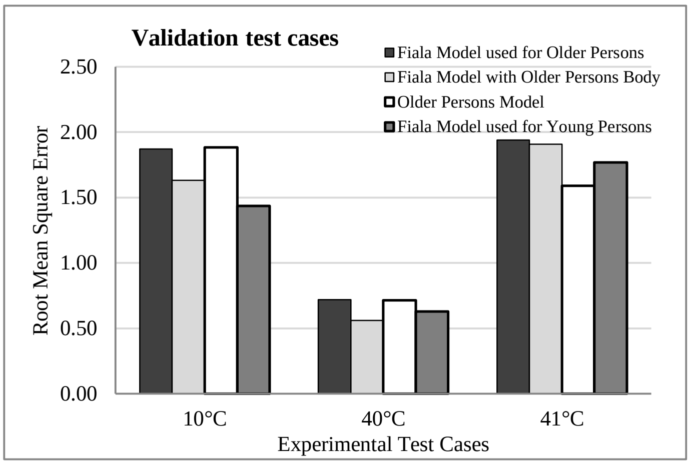

Figure 6.29 Root mean Square Error for Validation test cases

Figure 6.29 show the root mean square error (RMSE) plots for the test cases used in the validation of the model. Figure 6.29, show mixed results of the models with Fiala model used for younger persons prediction recording a better RMSE than all the other models in test case 10°C but in test case 40°C the results of Fiala Model with older person's body were better. In test case 41°C, the Older Persons Model recorded a better

RMSE than all other models. Fiala Model used for younger persons however had mixed results with test cases 40°C and 41°C. These results bring up the issue of how sensitive the model is to the mean skin temperature since all the root mean square error of the models being analysed for mean skin temperature were all high as compared to that of the body core temperature. Even in the case of the Fiala Model used for predictions for younger subjects, some of the RMSE's were high.

Clearly the validations results show that, whiles the Older Persons Model predictions for the core temperature were in very good agreement with measured data that of the mean skin temperature shows some limitations. Section 6.8 discusses some of the issues which may have contributed to the occurrence of these deviations in the predictions of the model.

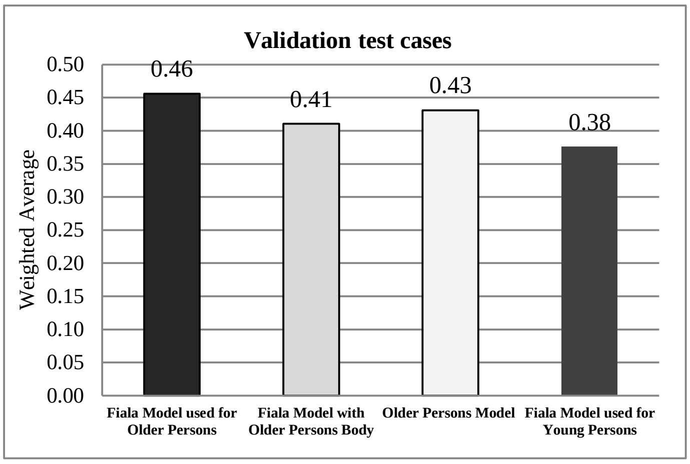

Figure 6.30 Weighted Average for Validation test cases

Figure 6.30 show the weighted average of the RMSE. This was calculated using equation 6.4 for each test case's RMSE. Figure 6.30 reveals that the Older Persons Model appears to have recorded high values as seen in the individual cases. On the other hand, the results of the Fiala Model with older person's body show that, modifying the passive system did compromise the mean skin temperature behaviour of the model. These results raise questions about the predictive capabilities of the Fiala model in terms of predicting for the mean skin temperature. Indeed in a comparative analysis involving the use of Fiala Model for young person's predictions, the calculated weighted average was 0.38 as against 0.43 for the Older Person's Model and 0.45 for Fiala Model used for older person's and 0.41 for Fiala Model with older person's body.

6.6.3 Overall Mean Skin Temperature Statistical Evaluation

Figure 6.31 shows the average values of the RMSE for the entire data sets used in the mean skin temperature calibration and validation. As has been reported in the various test cases, the comparative predictive capabilities of the various models under considerations were not clear cut with all the models reporting varying values. In Figure 6.31 it can be observed that, whilst Fiala model used for the prediction of older persons recorded RMSE values of 1.61 which was quite similar to that of the Older Persons Model (1.62), the value for the Fiala Model with older person's body was 1.44.

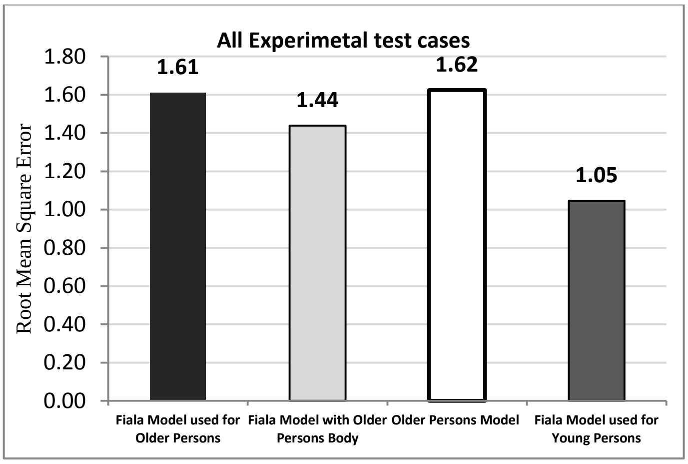

Figure 6.31 Average Root Mean Square Error for All Experimental test cases

For Fiala Model used for young person's predictions, the RMSE's was 1.05 which was quite better than other models values. The same trend can be observed in the contest of the Weighted Average of the RMSE, Figure 6.32.

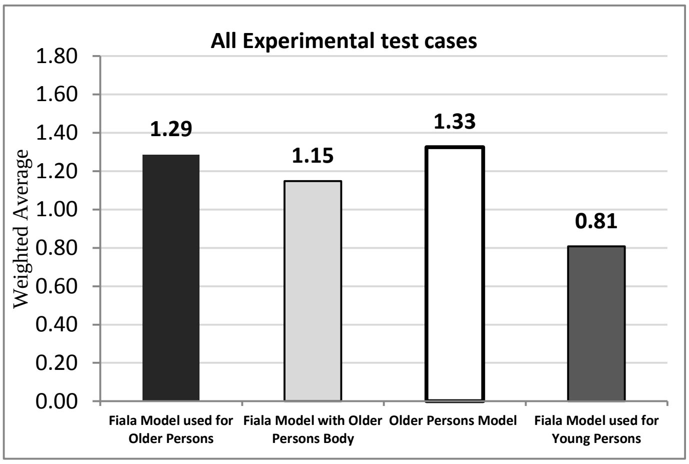

Figure 6.32 Weighted Average (WA) for experimental test cases

Looking closely at these results, one thing which stands out was that, the statistical metrics of RMSE and Weighted Average values in the contest of the mean skin temperature were higher compared to the core temperature. Table 6.2 shows the list of other statistical values calculated from the predictions of the models. These include the maximum residual errors ($e$max) and minimum residual errors ($e$min), the mean average deviation, the coefficient of determination and the 95 percentile.

Table 6.2 Comparison of statistical Metrics for mean skin temperature

Statistical Evaluation Table - Mean Skin Temperature (T_{skm})				
	Fiala Model used for Older Persons	**Fiala Model with Older Persons Body**	**Older Persons Model**	**Fiala Model used for Young Persons**
Root Mean Square Error	1.61	1.44	1.62	1.05
Weighted Average	1.29	1.15	1.33	0.81
$e$max	2.79	2.72	2.06	2.43
$e$min	-2.51	-2.51	-2.60	-4.17
Mean Average Deviation	1.17	1.00	1.20	0.90
R^2	0.86	0.89	0.87	0.90
95 percentile	2.37	2.35	1.92	1.87

The Fiala Model with older person's body has the highest coefficient of determination (0.89) with a mean average deviation of (1.00) when compared to other models. This reveals that, the predicted mean skin temperature values calculated by the model are closest to the observed data. However, the Older Persons Model had coefficients of determination (0.87) and a mean absolute deviation of (1.20). Furthermore, from Table 6.1, Fiala Model used for older person's had a coefficient of determination (0.86) and a mean absolute deviation of 1.17. These results show that, the predicted values of the model were not that different from the other models.

In a comparative analysis in the context of their prediction for mean skin temperature in their respective fields of application, Fiala Model has coefficient of determination (0.90) and mean average deviation of (0.90) showing that, the predicted values calculated by the model are close to the measured experimental data of young subjects. Comparatively Older Persons Models calculated values (coefficient of determination (0.87) and mean average deviation (0.12)) reflect the correlation between the predictive capabilities of these models in their individual fields. However the Fiala

Model with older person's body results correlates better. From Table 6.2 it can be seen that the results of the maximum residual ($e$max) and minimum residual ($e$min) of the models were quite similar. However, the Older Persons Model has the narrowest range. The calculated 95 percentile values indicate that the Older Persons Model value of 1.92 reflects a better distribution of its results compared to other models (Fiala Model with older person's body (2.35) and Fiala Model used for older person's (2.37)).

6.7 Summary for Mean Skin Temperature

In analysing the predictive capabilities of the mean skin temperature predictions of the Older Persons Model, it was realized that there are limitations. Clearly the predictive capabilities of the core temperature are better than that of the mean skin temperature. Section 6.8 discussions some of the issues which may have contributed to the occurrence of the deviation in the results of the model.

6.8 Limited predictive ability of the model for Mean Skin Temperature

After many series of optimisation runs were carried out in search of the best fit coefficients for the Older Persons Model, it was discovered that, the predictive ability of the model in terms of mean skin temperature was limited. During the modification process whiles the predictions of the core temperature of the new model kept improving, that of the mean skin temperature appeared to be facing some challenges. Further optimisation was carried out with emphasis on the parameters involved in the skin control signal by (either increasing or decreasing the search space) to enable the optimisation programme find to the best fit coefficient's to be used. After several optimisation runs the current set of coefficients were arrived at even though there were still some limitations in the models ability to effectively predict the mean skin temperature. This shows that there are underlying issues which may be affecting the process. This situation was further interrogated and it was discovered that several factors may have accounted for or played a role in the occurrence of this situation. These issues and factors have been discussed below:

Limited data set and Number of test subjects: The current research encountered many problems with regards to collation of appreciable amount of experimental data for the modification of the Fiala Model. Indeed whiles Fiala model used in excess of 20 experiments involving over 2000 subjects, the current research was only able to collate in total 15 relevant and related experiments involving 163 subjects due to the difficulty in getting published experimental data on older people. Nevertheless diligent effort was made to extract relevant information from the available data sets for the calibration and validation of the model. In relation to the current data sets, 12 test cases with 155 test subjects had data sets for the core body temperature while for the mean skin temperature only 7 test cases with 72 subjects had data sets. This is relatively a small number to use for the modification of a population based model. This limited data set may have played a role on affecting the predictive ability of the model in terms of the mean skin temperature.

Limited information about test cases: During the review and analysis of the collated experimental data sets, one of the challenges faced was the inconclusive nature of some of the information about the test cases in published literature. Indeed this is not to say that the author's deliberately left out some useful information but rather in most cases, the experiments' were not designed to be used for modelling purposes. As such even though the authors may have had access to some of this vital sets of information, it may not have been critical to report it in the context of their work. For example, some of the test cases did not report on the environmental exposure of test subjects before they enter the test chamber. Some also, did not report on the rate of air movement (velocity) and humidity before or during the test and some of these values had to be selected by the researcher based inferences from other test cases. Indeed, it is well established that environmental conditions affect most importantly the mean skin temperature than the core temperature and these varying discrepancies in the test conditions have the likelihood of affecting the models behaviour. Indeed this justifies the need for specific test cases to be designed for the older population so that all the needed data sets could be captured.

Skin Contact with surfaces: In most test cases, the subjects are reported to be seated in a relaxed position but as to the type of materials their sits are made of and the percentage of their body surface in contact with the sit were not given. The current research did not take into consideration the likely effect of the interaction between the sit and the subject’s skin and its implications for the mean skin prediction due to more insulation. This may also have some influence on the outcome of the mean skin temperature predictions of the Older Persons Model.

Skin Temperature Measurement: In measuring the mean skin temperature, there are various formulas used which are based on the number of sites on the body. Whiles, original Fiala model used 15 sites on the body for the evaluation of the mean skin temperature, some of the test experiments used lesser number of sites and others did not report on the number of sites used in their evaluation. Test cases 12°C, 17°C used 9 sites and 18°C and 27°C used three sites. This varied use of formulas in determining the mean skin temperature may also have some degree of errors in the data sets used for the mean skin temperature validation and calibration.

Sensitivity of the skin: According to Stevens and Choo (1998) thermal sensitivity of the skin decreases over the age of a person, and taking cognizance of this finding, it can reasonably be concluded that, the coefficients of skin sensitivity used in the original Fiala model may not be the same for the older person. In the current research, the likely reduction of skin sensitivity is not considered because there appears to be limited data for older people. This may potentially have effect on the output of the skin temperature of the model.

6.9 Summary of the Chapter

In this chapter, statistical metrics were used to evaluate the predictive capabilities of the Older Persons Model in comparison with the Fiala Model used for predicting for older persons, Fiala Model with older person’s body composition and Fiala Model used for younger subjects. Core temperature predictions of the Older Persons Model were better than that of the Fiala Model used for older person’s prediction and the Fiala Model with older person’s body composition. However, mean skin temperature predictions of the Older Persons Model did not agree well with experimental data in comparison with core temperature predictions. Some of the issues which may have contributed to this occurrence were discussed.

Chapter 7

Model Application and Discussion

7.1 Introduction

This chapter is divided into two parts as outlined in Figure 7.1: In part 1 extensive literature search was conducted to extract relevant information on thermally stressful environments older people may be exposed to and other practical research findings on human thermal behaviour. These findings were used to design representative test case scenarios which were simulated using the Older Persons Model. In some cases, the Fiala Model was also used for comparison purposes. The results of the Older Persons Model were analysed to establish the models agreement with published research findings.

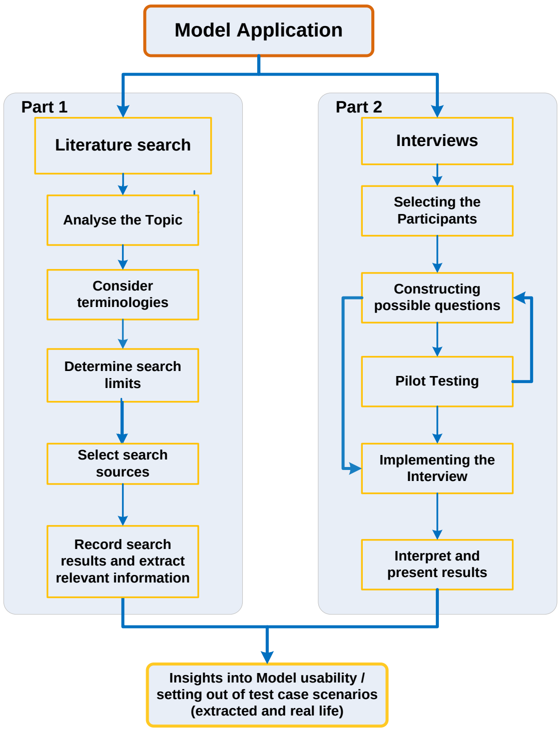

Figure 7.1 Model application framework

In part 2, semi-structured interview study was conducted aimed at gathering information on potential application of the Older Persons Model from selected professionals.

7.2 Literature search

A detailed literature search was conducted and all related search results were tabulated and relevant information extracted for implementation. Below is the outline (method) adopted in carrying out the search and Table 7.1 shows a list of the selected publications.

- <u>Analyse the Topic</u>

Detailed analysis of the topic under consideration was undertaken in chapters 1, 2 and 3 and this provides a sound base for the literature search to be carried out.

- <u>Consider terminologies:</u>

Since this search focuses on situations and scenarios which could be implemented in the model to test its wider applicability, terminologies such as ageing and thermal comfort, temperature and older people are included.

- <u>Search limits determinants</u>

The limit used in the search is the age of the publication which was set at after year 2000.

- <u>Select search sources</u>

The sources of the search included Journals, conference papers, articles, theses, handouts, and books

- <u>Record search results and extract relevant information</u>

The related search results were tabulated (Table 7.1) and the relevant information from these studies were used to design test case scenarios to reflect some of the situations as reported in the various publications (Ooka et al., 2010, Goodwin, 2011, Brown, 2010)

Table 7.1 List of the selected publications and case scenarios developed.

No.	Authour & Year	Title of Publication	Type of Publication	Information Extracted	Test Case Senarios
1	**Goodwin (2011)**	Expert Briefing Winter Warmth-Age Uk Knowledge Hub -Winter Cold And Health Everything You Wanted To Know But Didn't Dare Ask	**Confference paper**	**1.** Moving from a cold home to outside cold carries significantly more risk to health than moving form a warm room. **2.** There are trigger sites on the human body example hand, feet, face and head which facilitates thermal accidents. **3.** Body temperature core and skin fall quickly on exposure to cold **4.** Moderate level of activity reduce the risk of body cooling	**1.** Ta=28 to 5°C, va = 0.5, RH = 50%, act = 1 met 2. Ta=20 to 5°C, va = 0.5, RH = 50%, act = 1 3. Ta=28 to 25°C, va = 0.5, RH = 50%, act = 0.8 &1.6 met
2	**Fiala (1998)**	Dynamic Simulation of Human Heat Transfer and Thermal Comfort	**Thesis**	1. Changing environment	4. Transient temp of Ta=43-17-43°C, va = 0.12, RH = 30%, act = 1 met
3	**Ooka 2010**	Improvement of sweating model in 2-Node Model and its application to thermal safety for hot environments	**Journal Paper**	1. Two (2) room senarios of different temperature profiles	5. Ta=35°C, va = 0.1, RH = 50%, act = 1 met 6. Ta=35°C, va = 0.1, RH = 70%, act = 3 met
4	**Brown (2010)**	In The Heat of Power: Understanding Vulnerability to Heatwaves in Care Homes for Older People.	**Thesis**	**1.** Residents are exposed to excessively high temperatures through the action of disciplinary power which seeks to control and reform residents by holding them in place	1. Ta=28-35-45°C, va = 0.1, RH = 50%, act = 1 met

7.3 Test Case 1 & 2

- Moving from a cold home to outside cold carries significantly more risk to health than moving from a warm room.
    - *"Body core temperature and skin fall quickly on exposure to cold"* (Goodwin, 2011)

In the first scenario, the model subject (older person) was exposed to varying ambient temperature of a room at 28°C for 60 minutes where the subject was sitting (1 met). Afterwards the subject moved into a room with an ambient temperature of 5°C with the same activity level for 120 minutes. In second scenario, the subject before moving into the cold room of 5°C for 120 minutes stayed in the room with 20°C ambient temperature for 60 minutes. Other details of the test cases are given below.

Test Case 1 - Ta=28 to 5°C, va = 0.1, RH = 50%, act = 1 met

Test Case 2 - Ta=20 to 5°C, va = 0.1, RH = 50%, act = 1met

Simulation results

Figure 7.2 shows the plot of the test cases 1 & 2 results for the Fiala model and the Older Person's Model.

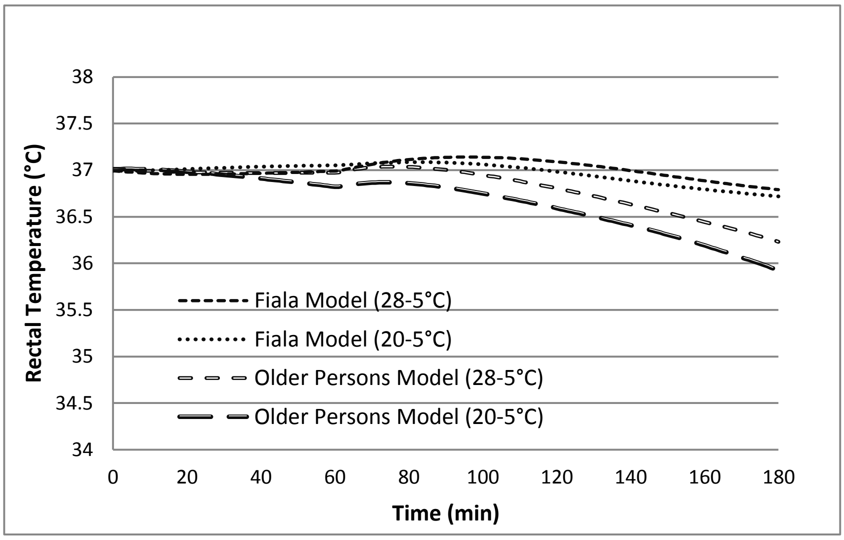

Figure 7.2 Test case 1 & 2 core body temperature results

From visual inspection of the graph, it can be observed that while the core body temperature prediction of the Fiala model was fairly constant in both test case scenarios that of the older person as predicted by the Older Persons Model show otherwise. In test case 1 where the model subject (older person) moved from a room of temperature 28°C to a cold environment of 5°C with clothing insulation of 1.5clo, there was a minimal rise in core body temperature before it began falling after 20mins upon entering into the cold environment. The fall in core body temperature continued until the end of the test experiment (120min). In test case 2 where the starting temperature in the room was 20°C even before the test subject moved into the cold environment of 5°C, the subject already had a slightly reduced body core temperature of 36.82°C which represents a 0.18°C decrease from the base line core temperature of 37°C. On exposure to the cold environment further, there was a progressive fall in the body core temperature over the duration of the experiment giving credence to what Goodwin (2010) stated that, upon exposure to cold environment the core body temperature of the older person fall rapidly.

Figure 7.3 shows the end of experiment temperature values for the core body temperature. In test case 1, the prediction for Older Persons Model was 36.23°C representing a 0.77°C fall from the baseline temperature of 37°C but for test case 2, the temperature was 35.93°C representing a greater fall of 1.07°C from the original baseline value of 37°C. However in the same test cases, Fiala Model's prediction for test case 1 was 36.79 representing 0.21°C fall from the base line temperature. Furthermore, in test case 2 the temperature at the end of the test was 36.72°C representing 0.28°C fall from the base line temperature of 37°C. Indeed many research findings have pointed out the reduced heat generation capability of the older person and in this case, there appears to be a distinctive lack of capability of the older person body system to effectively generate enough heat to keep the body warm in the cold.

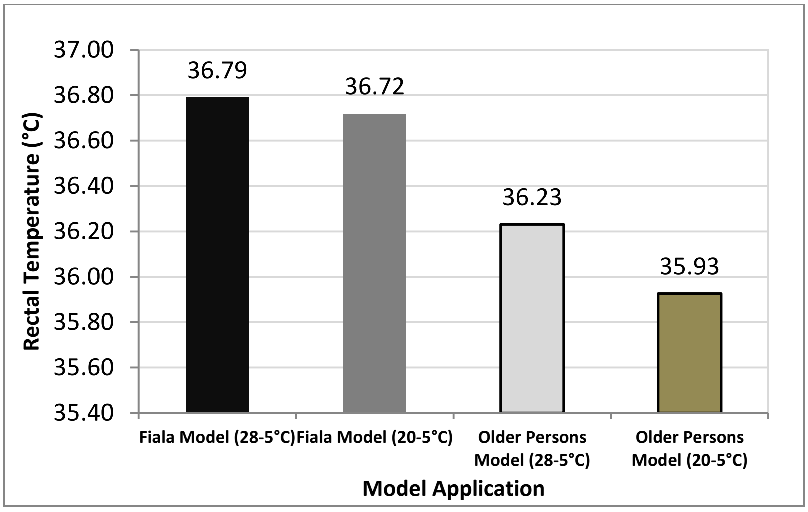

Figure 7.3 Test case 1 & 2 end of experiment body core temperature

Figure 7.4 shows the plots of the mean skin temperature at the end of the experiment. For the Fiala model, the temperature value in test case 1 was 27.26°C representing 7.74°C fall from the set point mean skin temperature at the start of the experiment of 35°C. In test case 2, the final temperature value was 26.97°C representing a decrease of 8.03°C from the initial set point temperature of 35°C. Indeed the test results show that even in the case of the average person, there was a reduction in the mean skin temperature upon exposure to cold. A look at the predictions for the older person reveals a greater degree of fall in the mean skin temperature of test case 2 subject than test case 1. In test case 2, the end of test temperature reading was 26.87°C representing 8.13°C fall whilst that of the test case 1 was 27.12°C representing a 7.88°C fall from the set point of 35°C. These values were lower than that of the average person thus agreeing with what literature says that body temperature cooling in the older person is more pronounced than in the younger person. Indeed Figure 7.5 shows results of the various body locations which gives a clearer picture of the mean skin variations in on the human body.

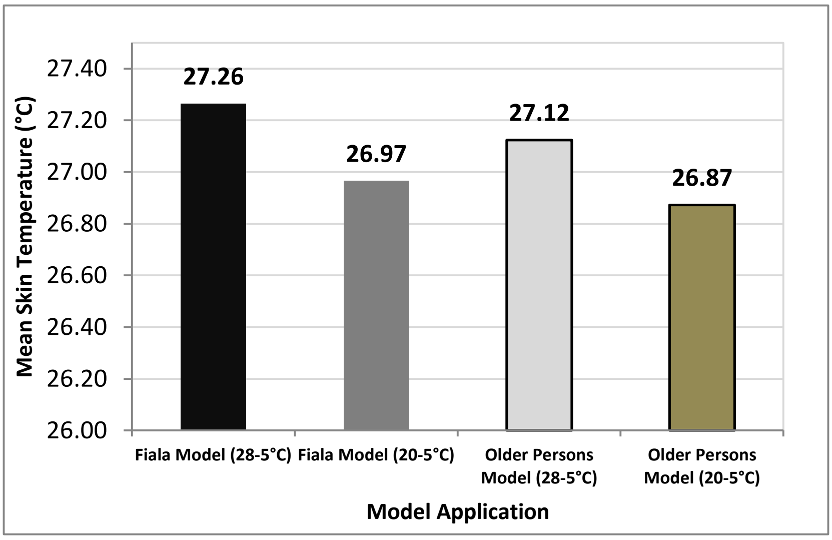

Figure 7.4 Test cases 1 & 2 end of experiment mean skin temperature

From Figure 7.5 it can be observed that the back of the hand in both tests cases appears to be the body part with the lowest skin temperature amongst the body parameters plotted. In the two test cases, it can also be observed that the body location readings were higher in the test case 1, which involved moving from a room temperature of 28°C to cold environment than moving from room temperature of 20°C to a cold room of 5°C.

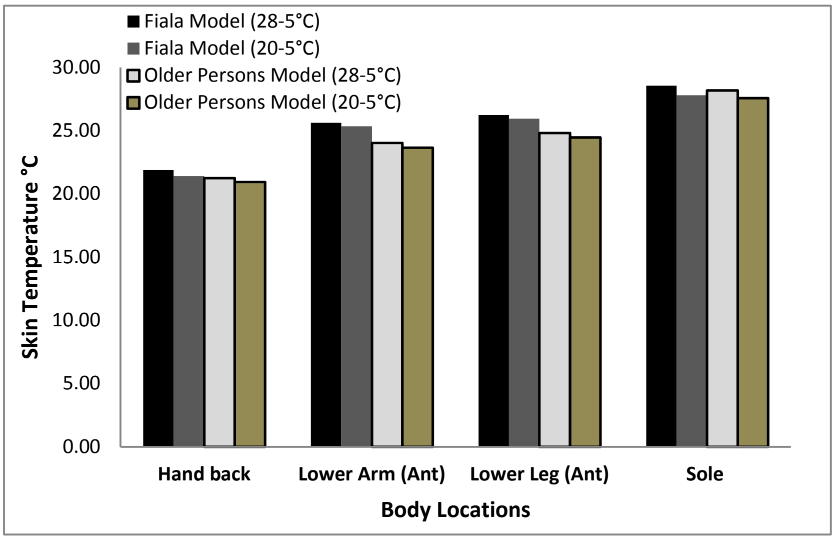

Figure 7.5 End of experiment skin temperature selected body parts (test case 1&2)

From Figure 7.4 the end of test mean skin temperature in test case 1 for the older person was 27.12°C but the body locations values differ for example (Figure 7.5) the back of hand had 21.24°C and the lower arm had 24.03°C whilst the sole and the lower leg had 28.19°C and 24.81°C respectively. In test case 2 however, the temperature at the back of the hand was 20.94°C and the lower arm had 23.66°C whilst the sole and the lower leg had 27.58°C and 24.47°C respectively. These results confirms Godwin (2010)'s assertion that there are trigger sites on the human body which facilitates thermal accidents and the Older Person's Model appears to have reasonably predicted these phenomenon.

7.4 Test Case 3

"Moderate level of activity reduces the risk of body cooling" Goodwin (2011). This test scenario was simulated using only the Older Persons Model. It was assumed that the model subject (an old person) was exposed to varying ambient temperature of 28°C for duration of 30mins in a sitting and relaxed position with activity level of 0.8 met. Afterwards the subject moved into a room with an ambient temperature of 25°C with the same activity level for 240 minutes. In the second scenario of the same experimental set up, the subject after staying in the room with temperature of 28°C for 30 minutes moved to another the ambient temperature of 25°C but this time undertook intermittent exercise of (1.6met) after each 20 minutes of rest (Figure 7.6).

Test Case 3 - Ta=28 to 25°C, va = 0.5, RH = 50%, act = 0.8 &1.6 met

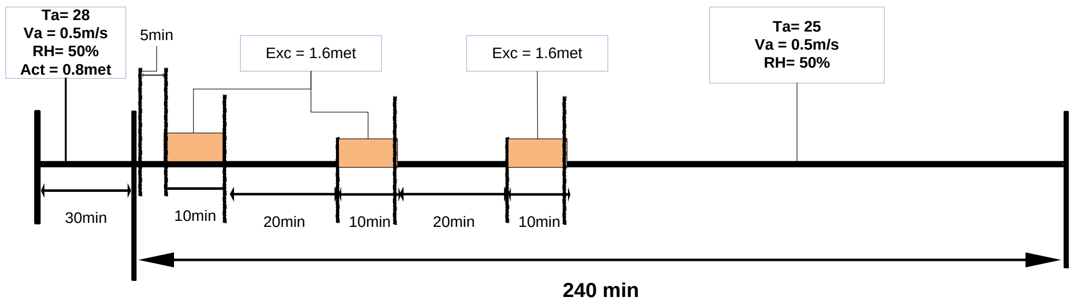

Figure 7.6 Test case 3 representation

Simulation results

From Figure 7.7, it can be observed that, the Older Persons Model results for exposure without intermittent exercise show a constant core body temperature during the baseline setup. However, 10 minutes upon entering the test environment of 25°C the core temperature began to fall.

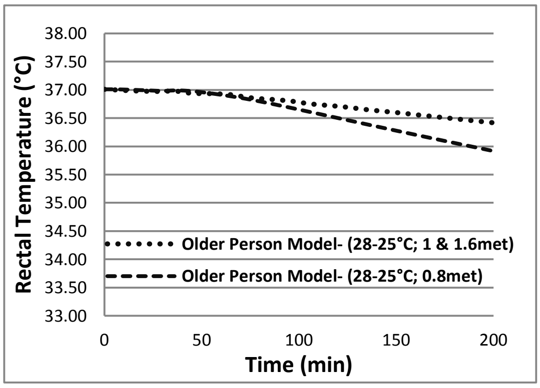

Figure 7.7 Rectal temperature of 28-25°C exposure

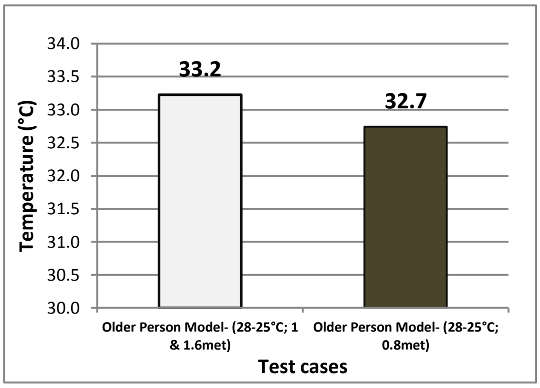

Figure 7.8 End of test (3) mean skin temperature

This trend continued until the end of the test with body core temperature of 35.54°C which represents a fall of 1.46°C from the base line temperature. However, in the experiment with intermittent exercise, even though there was a fall in the body temperature over the duration of the experiments the recorded end of test core body temperature was 36.22°C, which represents a fall of only 0.78°C from the baseline. This phenomenon lends credence to the advice given to many older persons by health authorities including National Health Service(NHS) United Kingdom that whiles at home it is beneficial to once a while get up walk and since moderate level of activity reduces the risk of body cooling. Figure 7.8 shows the mean skin temperature variations of the two test scenarios with the case without intermittent exercise recording and lower result.

7.5 Test Case 4

Changing environment (Fiala, 1998)

Experimental test case 4 was one of the test cases used in validating the Fiala Model (1998). This test involves the transient change in temperature of the environment from hot to cold and back to hot (43-17-43) °C. The exposure for hot summer day of 43°C lasted for 60 minutes whilst that for the cold environment lasted for 120 minutes and the second hot exposure lasted 60 minutes accounting for 240 minutes total duration. Figure 7.9 shows the details and profile of test case 4. Clothing insulations was estimated to be 0.6clo.

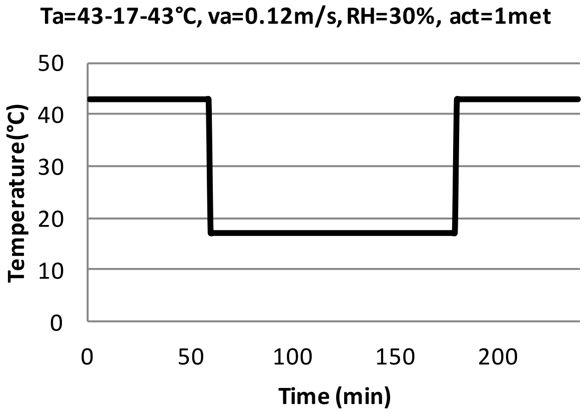

Figure 7.9 Test case 4 temperature profile

Simulation results

This test experiment was adapted for use to test the Older Persons Model's ability to predict for the older person in changing environmental exposures.

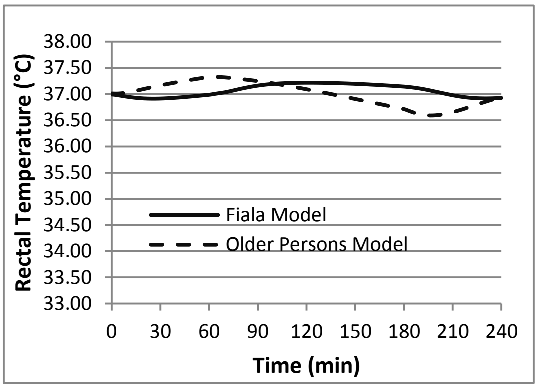

Figure 7.10 Rectal Temperature (test case 4)

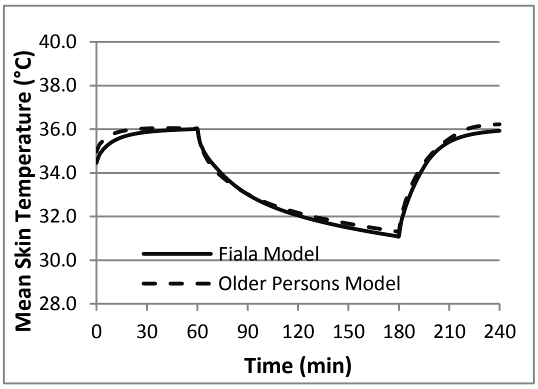

Figure 7.11 Mean skin temperature (test case 4)

It can be seen from Figure 7.10 that, the Fiala models results from the baseline core temperature (37°C) deviates slightly in the exposure to the cold temperature of 17°C but was relatively within the range of (36.91 to 37.22)°C for both heat and cold exposures. In the case of the Older Persons Model, from the baseline temperature of 37°C after 20 minutes into the experiment the temperature began increasing to (37.1°C) over the test environment of 43°C peaking at 37.33°C before the cold exposure. This shows that at this point should the older person be exposed to more hot temperature for long, the body was likely to overheat. Upon exposure to the cold (17°C) the temperature from the peak point (37.33°C) starts to fall after 15 minutes. This trend continued over the entire exposure to the cold of 17°C. Upon entering into the hot exposure of 43°C, the temperature kept falling for 20 minutes reaching a low point of 36.59°C. This shows that at this point should the older person be continuously exposed to cold temperatures, the body was likely to over cool. After 20 minutes in the 43°C exposure, the temperature of the body starts to increase to the original core body set point temperature of 37°C. These results show that the older person's body does not immediately warm up upon entering into the hot environment after exposure to cold. This may be attributed to widening of the null zone (Appenzeller et al., 1999) which is associated with the lowering of the cold threshold and elevations of the heat threshold in the older person. Figure 7.11 shows the plot for the mean skin temperature of both the Fiala model and Older Persons Model reflecting the correlative predictive capabilities of the two models.

7.6 Test case 5 & 6

Two (2) room scenarios of different temperature, humidity and activity exposures (Ooka et al., 2010). In Test Case 5, the model test subject was exposed to a room temperature of 35°C with an activity level of 1.0 which was achieved by sitting in a chair. Test case 6 was designed by the author (Ooka 2010) to test effect of increased activity, high temperature and high humidity on the thermal behaviour of test subjects. In this section, the Fiala model and the Older Person's Model were used to simulate these cases and the results plotted in Figure 7.13 and 7.14. Other details of the test cases are given below.

Test case 5 - Ta=35°C, va = 0.1, RH = 50%, act = 1
Test case 6 - Ta=35°C, va = 0.1, RH = 70%, act = 3

Simulation results

These case studies were used in this research to explore the varying thermal situations which may likely confront older persons. The application of the Older Persons Model provides the opportunity to analyse the likely thermal behaviour of older persons in these conditions. It can be seen from Figure 7.12 that, from the beginning of the test case, the core temperature measurement for both Fiala Model and Older Persons

Model began from the same point, but about 1mins into the test older person appears to have begun storing of heat which makes the body core temperature begin to increase above the base line of 37°C minimally.

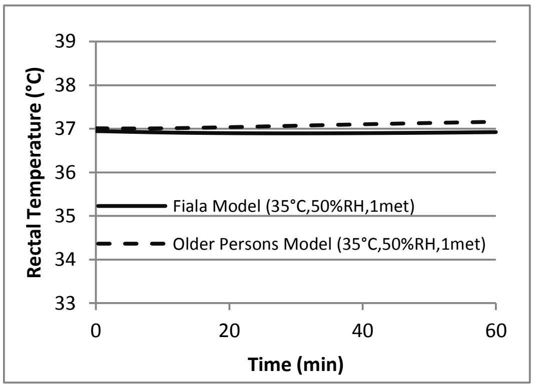

Figure 7.12 Rectal Temperature (test case 5)

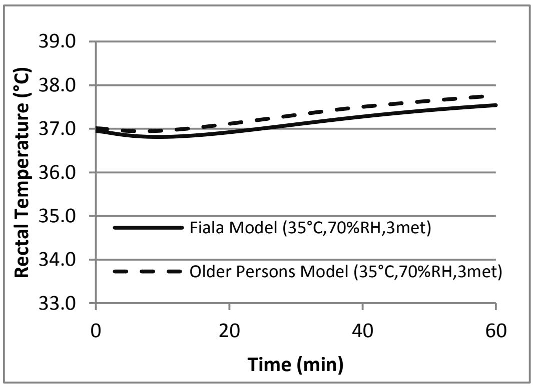

Figure 7.13 Rectal Temperature (test case 6)

Even though it may not have deviated that much, the model was able to point out the likely thermal reaction of the older person. At the end of the experiment, the core temperature for the Older Persons Model was 37.16°C. However, the Fiala models predictions were quite constant over the test period recording an end of test body core temperature of 37°C. However in test case 6, from Figure 7.13 it can be seen that, after 20 minutes in to the test, the combination of high relative humidity and high temperature the, core body temperature of the older person according to the Older Persons Model prediction was likely to increase steadily recording an end of experiment value of 37.8°C. This represents a 0.8°C increase from the base line value of 37.0°C. This invariably, appears to be pointing to an issue of overheating to be experienced by the older person. On the other hand, the Fiala models results increased from the base line after 30 minutes and recorded an end of experiment body core temperature of 37.5 which represents a 0.5°C increment but well within the thermal safety limits.

7.7 Test case 7

High temperature exposure of older persons (Brown, 2010);

"Residents are exposed to excessively high temperature through the action of disciplinary power which seeks to control and reform residents by holding them in place"

Even though it may not be possible for the older person to be exposed to severe environmental temperature of 45°C due to many preventive measures and warning systems available, the Older Persons Model provides a unique opportunity for researchers to test the likely effect of various temperature variations without exposing an older person to harm. In this test scenario, the model subject was exposed to varying ambient temperature of (28-35-45) °C of 60 minutes duration each with an activity level of 1 met; figure 7.14 shows the test representation.

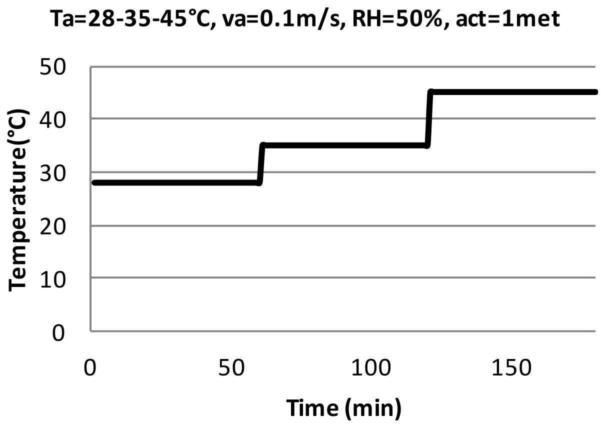

Figure 7.14 Test case 7 temperature profile

Simulation results

From Figure 7.15, it can be seen that there was a gradual increase in the body core temperature upon entering of the subject into the 45°C environmental exposure predicted by the Fiala model. The exposures of 28°C and 35°C did not cause any marginal increase in the body core temperature. The trend of temperature rise in 45°C predicted by Fiala model continued until the end of the test with the end of test temperature reading of 37.37°C. In contrast, the predictions of the Older Persons Model show a gradual increase in core body temperature after 30 minutes in 35°C exposure and this continued upwards until the end of experiment with final recorded body temperature of 37.59°C. From Figure 7.15 it can be observed that, the likelihood of overheating occurring in the older person was high when exposed to very high temperatures as indicated by Brown (2011).

These results from the Older Persons Model are expected to further assist in better understanding the thermal responses of older persons and how to manage their thermal needs and expectations.

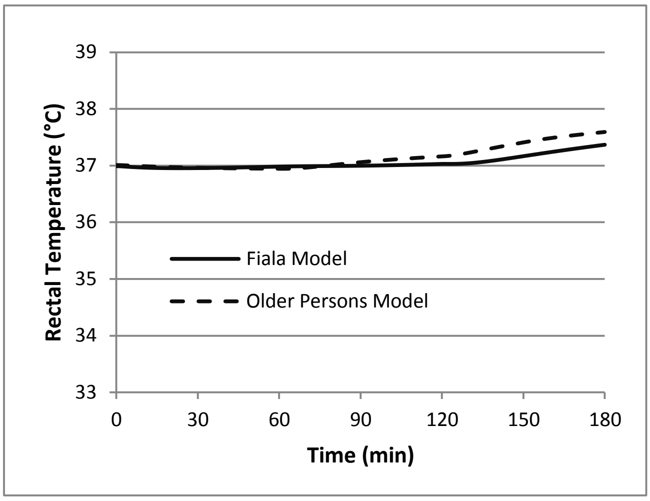

Figure 7.15 Rectal temperature (test case 7)

7.8 Summary of observations

In carrying out the model application procedure the researcher sort to test the wider application/utilization of the model and how its results support available research findings and information on the thermal behaviour and response patterns of the older person. In all the test cases simulated, the Older Persons Model shows reasonable agreement with published information on the thermal state and responses of the older person. The model also displayed good predictive capability in correlation with the Fiala model reflecting its strong predictive capabilities. Indeed, as stated in the Chapter 6, there are limitations in the current model but the current version has been shown in this research work to predict with a reasonable degree of accuracy the thermal behaviour of the older person. The current model is an addition to the currently used average person's thermoregulation models whose results have in fact been shown to be closer to the experimental results of the younger person than the older person (see Chapter 6).

7.9 Interview Study

In addition to the development, validation and application of the model, issues regarding the usability of the model were explored in an interview study. This section outlines the aim of the interview, the method used, the principal findings and a short discussion on the findings. Qualitative research interviews seeks to understand something from the subject's point of view allowing then to convey to others their own perspective and in their own words (Kvale, 1996). Interviews take different forms which include fully structured, semi-structured and unstructured interviews. Fully structured interviews are often common with quantitative research where the objectives are predetermined. In this type of interview, the interviewees are asked the same set of questions which produces data which can be statistically analysed. Semi-structured interviews however have predetermined questions but the order can be modified based on the interviewers perceptions of what is deemed appropriate and from the response of the interviewees (Coley, 2008). This allows some degree of freedom and adaptability.

In unstructured interviewing, the researcher approaches the interview with no pre-defined theoretical framework of the topic under investigation but engages in conversation with the interviewee and generates questions in response to the interviewees' narration (Zhang and Wildemuth, 2009) . Such an open ended questioning encourages free expressions on the part of the interviewee thus generating a rich form of descriptive data (Coley, 2008). In order to achieve deep insight into people's lives the researcher needs have a detailed knowledge and adequate preparation before conducting the interview (Patton, 2002). At all times the research needs to keep in mind the purpose of the study and the general scope of issues to be discussed (Fife, 2005). In this study, the semi-structured interview format was adopted.

7.10 Aim of the interview study

The interview study was carried out as part of the methodology set out at the beginning of the research. Its aim is to introduce the final model to a selected group of professionals (mechanical engineers, building services specialist and designers) and to elicit their views on the potential application of the model. Through this engagement; the researcher sought to, reduce the threats to the validity of the model by ensuring that some professionals have had the opportunity to review and comment on the model and some of its output. Below is the outline (method) adopted in carrying out the interview.

- *Selecting the Participants*
- *Constructing possible questions*
- *Pilot Testing*
- *Implementing the Interview*
- *Interpret and present results*

7.11 Selection of participants

Six (6) individuals of varying backgrounds were interviewed. All the interviewees were recruited through previous contact and recommendation of colleagues and the supervision team. Sampling was purposeful (Maxwell, 2005), with an intentional focus on interviewing professionals whose work in one way or the other is related to providing suitable built environments for human occupations.

7.12 Constructing possible questions

Questions relating to ageing and human thermoregulation modelling were formulated by the researcher and discussed with the supervision team. Modifications were made and sets of questions to be used as a tool to guide the discussions were agreed upon. Appendix F shows a set of sample questions.

7.13 Pilot Testing

A pilot interview was conducted with a building simulation expert who has frequently used human thermoregulations models in his field of work. The aim of the pilot testing was to trial test the interview to find out whether questions were enough and how prepared the interviewer was. The results of the pilot interview highlighted issues which the researcher later addressed before the main interview. Some of these issues include:

- The right placing on the dictation machine to ensure clarity of recording.
- Selections of the right locations to avoid disruptions.
- The need to wait for complete answers from the interviewee before asking the next question.

- Re-framing of some of the questions.
- New questions to serve a guide to main interviews.
- The need to make the interviewee feel at home during the interview.

7.14 Implementing the interview

Thirty minutes (30 minutes) meetings were arranged with each participant consisting of 10 minutes of informal discussions and 20 minutes of recorded semi-structured interview where during the interview some test case results were shown to the interviewees. This was to enable them be acquainted with the predictive characteristics of the model.

7.15 Analysis

All interviews were transcribed by the researcher with data from each interview being analysed by identifying the main relevant themes that emerged. Themes can be described as the conceptual linking of expressions which comes from data available and the investigators prior theoretical understanding of the study being undertaken (Ryan and Bernard, 2003).

7. 16 Results

Results are presented for the main themes identified in the interview which includes general view about the model, model output and practical usefulness. Where quotations from the interviewees are used to support an idea, short descriptions of the area of expertise of the interviewees were used for identification. For example, BSS1 represents interviewee number 1 with area of expertise as Building Services Specialist. Table 7.2 provides the list of number of subjects interviewed.

Table 7.2 List of interviewees

No.	Description	ID
1	**Mechanical Engineer**	**MCE1**
2	**Mechanical Engineer**	**MCE2**
3	**Building Services Specialist**	**BSS3**
4	**Architect**	**AC4**
5	**Building Physicist**	**BP5**
6	**Building Services Engineer**	**BSE6**

7.16.1 General View about the model

During the interview, aspects of the general view about the older person model were raised. Often these responses were interlaced with how ageing of the world's populations would affect the way comfort in the built environment is satisfied.
Interviewee AC4 stated that:

"Developing a thermoregulation model for the elderly is an important topic since it is important to understand to a certain depth how the thermoregulatory systems apply to the elderly people".

Indeed Anderson et al.(1996) admits that as the body ages, functional changes occur which impact on the thermoregulatory system. According to Severens (2008) in the field of human thermoregulation there is consensus that, there is still more room for improvement in the analysis and prediction of the active system of the human body.
Interviewee BSS3 stated that;

"Knowing better about how the body reacts to changes in the thermal environment has useful implications in managing system 'heating systems' in a better manner which could help keep the bill down so reduces the chances of fuel poverty".

Indeed better control of the thermal environment to save on energy bill without compromising health and wellbeing is a critical issue when it comes to older persons.
From the interview results, the general consensus amongst the interviewee was that, the development of this model would assist in better understanding of the thermal behaviour of older persons with interviewee AC4 admitting that

"At *the moment I can't see a model that would be able to do this, so going in this direction to develop a working model for the elderly would be welcome".*

This veiw is supported by Someren (2007) who pointed out that, presently adopted models may require adaptations for them to be effective in ageing studies.

7.16.2 Model Output

Some generated outputs of the model were shown to the interviewees during the interview, some asked questions to further understand some of the results generated. Most of them (interviewees) were of the view that, the flexibility and dynamic nature of the model makes it a valuable tool. After a through perusal, they were of the view that different real life test cases could be simulated and the results used to support awareness creation campaigns on how to manage the thermal environment (heating control) in order to achieve comfort within budget without putting health at risk. Interviewee BSS3 stated that

"The predictions of the model can help in awareness rising not only for the older people but with other professionals with regards to how to keep people warm"

Since the threshold for the onset of thermal accidents for the older person is well noted and documented, the model results could provide a guide to better manage lifestyles in order to improve and preserve wellbeing with interviewee BP5 admitting that

"The results of the model could provide some guide as to how long the older person can be exposed to a specific condition e.g. taking a walk in winter condition without risking health".

7.16.3 Practical Usefulness

The models ability to predict the varying thermal response patterns of the human body in different environmental exposures was highlighted by the interviews as one of its strength. Practically the models results could help building services engineers obtain a clearer idea about priorities to focus on in providing comfortable environments for the older persons. Interviewee BSS3 explained that:

"In situations where it is identified that older person may not be able to manage or regulate effectively their heating demands, the models results can be used to reinforce the need to seek help in handling the situations in order to avoid risking health and wellbeing".

Interviewee BP5 suggests that;

"the model can be used to test how long it takes for an older person to recover to an acceptable state of core temperature after exposure to cold condition".

Interviewee MCE2 supported this view. Interviewee MCE1 recounted a real life thermal management of older persons in his home country (tropical climate). According to him

"Older persons are taken out in the morning to be warmed before being taken back into their rooms, apparently as a result of fall in the body core temperature overnight. He recalled that when he asked as to what informs them (carers) with regards to when to return them (older person) to their rooms after warming some replied from experience, or from friends' experiences or when the person complains. According to him, the results of the model could potentially help in better understating of the thermal behaviour of the older person and guide decision making in these real life scenarios".

Indeed many research publications have found reduced ability of older persons to detect changes in their thermal state as a result, they may largely not be aware that they are becoming ill from high temperature in order take action to reduce the exposure (Anderson et al., 1996, WHO-Europe, 2004, Farage et al., 2010). Barely relying on experience or views from friends also risks the life of the older person since literature points out that no two persons are the same both physically and physiologically. In agreeing with the interviewee, the result of the model could go a long way in better informing people who have connections with older persons to better manage their thermal conditions.

From the interview, it can be reasonable concluded that, the practical usefulness of the model has been appreciated by the interviewees. Most of the interviewees expressed their desire see results of combinations of different test cases which can serve as a quick reference guide.

7.16.4 Reflecting on the interview

After a thorough review of the interview results, the researcher reflected on some of the salient issues which came up during the interview. A prominent one was the interviewees recounting different ways people control their thermal environment (especially control of heating). Some of the interviewers (especially BSS3 and MCE1) suggested the simulations of some real life scenarios of thermal management profiles in homes which they have witnessed. Interviewee BSS3 suggested several scenarios which he believes if tested in the model and the results analysed can further add to the value of the research in shedding light on how best to manage thermal environments and how some of the current practices affect the thermal state of occupants. The researcher worked with the interviewees to narrow down the real life scenarios to seven test cases. Sections 7.18 describe the selected real life test cases.

7.17 Real life test cases

In all seven (7) test cases were designed based on real life experiences and observations of some of the interviewees on how people maintain and manage their thermal environments. In Test Case 1, an Older Person stayed in a room with temperature 22°C before changing into a winter wear (1.5clo) and heading out into the cold (temperature 7°C) for a walk which lasted one hour (60min). Whilst out and about, the room temperature was maintained at 22°C. Upon return to the room from the walk, the older person removed the winter wear and put on clothing with insulation value of 0.6clo. The older person then stayed in the room for 3 hours watching TV. Figure 7.16 shows the test temperature profile. In Test Case 2, an Older Person stayed in a room with temperature 22°C before changing into a winter wear (1.5clo) and heading out into the cold (temperature 7°C) for a walk which lasted one hour (60min). Before going out for the walk, the older person programmed the heating system to heat the room to 26°C before returning from the walk. Upon entering the room the older person allowed the temperature to remain at the 26°C for an hour before re-programming the thermostat to gradually lower it to 22°C over one hour. The older person then stayed in the room of 22°C for another hour with a clothing insulation of 0.6clo. Figure 7.17 shows the test temperature profile.

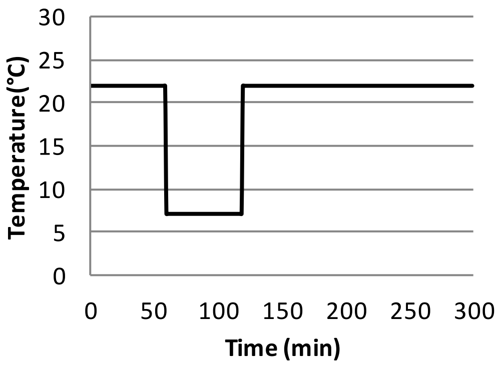

Figure 7.16 Temperature profile (test case 1)

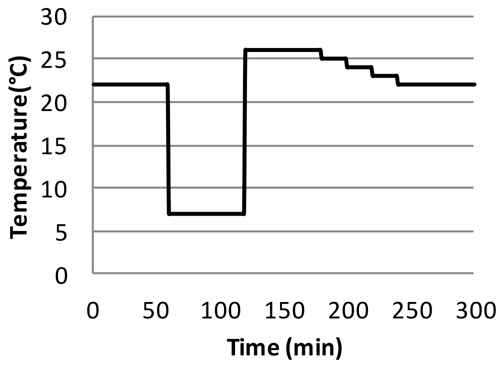

Figure 7.17 Temperature profile (test case 2)

In Test Case 3, the Older Person stayed in a room with temperature 22°C before changing into a winter wear (1.5clo) and heading out into the cold (temperature 7°C) for a walk which lasted for one hour. Before going out for the walk, the older person switched off the heating system to reduce the bills on heating. This resulted in the fall of room temperature from 22°C to 17°C during the time out (1hr). Upon return to the room, the older person programmed that thermostat to heat the room over one hour duration to 22°C. The temperature was then maintained at this level for 2 hours whilst the older person relaxed watching TV in a clothing insulation of 0.6clo. Figure 7.18 shows the test temperature profile. In Test Case 4, the Older Person stayed in a room with temperature 22°C before changing into a winter wear (1.5clo) and heading out into the cold (temperature 7°C) for a walk which lasted for one hour. Before going out for the walk, the older person programmed the thermostat to maintain the room temperature at 22°C. Upon return to the room, the older person re-programmed that thermostat to heat the room gradually over one hour duration to 25°C. The temperature was then maintained at this level for one hour before being allowed to fall over an hour to 22°C. During this time, the older person relaxed in the room watching TV in a clothing insulation of 0.6clo. Figure 7.19 shows the test temperature profile.

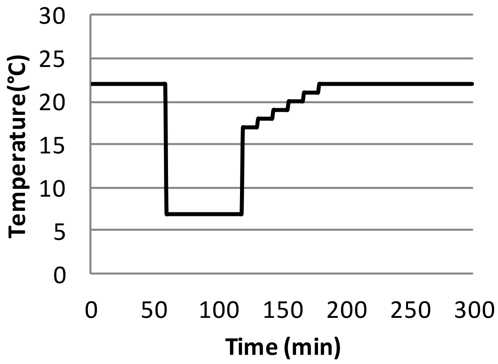

Figure 7.18 Temperature profile (test case 3)

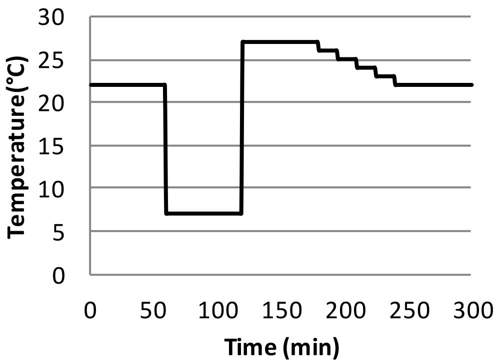

Figure 7.19 Temperature profile (test case 4)

In Test Case 5, however the Older Person stayed in a room with temperature 18°C before changing into a winter wear (1.5clo) and heading out into the cold (temperature 7°C) for a walk which lasted one hour (60min). Whilst out and about, the room temperature was maintained at 18°C. Upon return to the room from the walk, the older person removed the winter wear and put on clothing with insulation value of 0.6clo. The older person then stayed in the room for 3 hours watching TV. Figure 7.20 shows the test temperature profile.

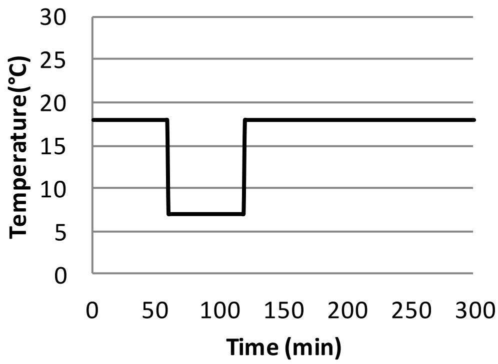

Figure 7.20 Temperature profile (test case 5)

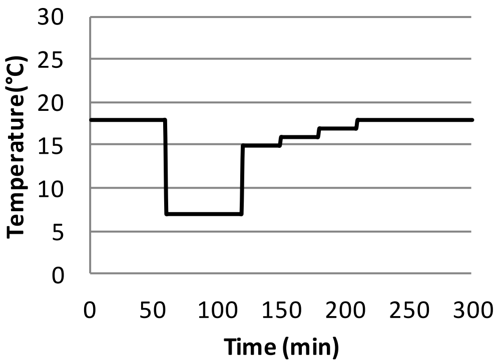

Figure 7.21 Temperature profile (test case 6)

In Test Case 6, An older person stayed in a room with temperature 18°C before changing into a winter wear (1.5clo) and heading out into the cold (temperature 7°C) for a walk which lasted for one hour. Before going out for the walk, the older person switched off the heating system to reduce the bills on heating. This resulted in the fall of room temperature from 18°C to 15°C during the time out (1hr). Upon return to the room, the older person programmed that thermostat to heat the room over one hour duration to 18°C. The temperature was then maintained at this level for 2 hours while the older person relaxed watching TV in a clothing insulation of 0.6clo. Figure 7.21 shows the test temperature profile. Test case 7 is a representation of test case 1 but with further clothing insulation (1.3clo) after 1 hour when the subject returned from the walk. Table 7.3 gives the detailed breakdown of the test conditions in the various cases.

Table 7.3 Selected test cases

	Test 1			Test 2			Test 3			Test 4			Test 5			Test 6			Test 7		
Room Description	Before Walk	Winter Outdoor	After Walk	Before Walk	Winter Outdoor	After Walk	Before Walk	Winter Outdoor	After Walk	Before Walk	Winter Outdoor	After Walk	Before Walk	Winter Outdoor	After Walk	Before Walk	Winter Outdoor	After Walk	Before Walk	Winter Outdoor	After Walk
Temperature (°C)	22	7	22	22	7	26 to 22	22	7	17 to 22	22	7	22 to 26 to 22	18	7	18	18	7	15 to 18	22	7	22
Velocity (m/s)	0.12	0.2	0.12	0.12	0.2	0.12	0.12	0.2	0.12	0.12	0.2	0.12	0.12	0.2	0.12	0.12	0.2	0.12	0.12	0.2	0.12
Relative Humidity (%)	50	60	50	50	60	50	50	60	50	50	60	50	50	60	50	50	60	50	50	60	50
Activity level (met)	1	1.6	1	1	1.6	1	1	1.6	1	1	1.6	1	1	1.6	1	1	1.6	1	1	1.6	1
Clothing (clo)	0.6	1.5	0.6	0.6	1.5	0.6	0.6	1.5	0.6	0.6	1.5	0.6	0.6	1.5	0.6	0.6	1.5	0.6	0.6	1.5	0.6 to 1.3
Duration (min)	60	60	180	60	60	180	60	60	180	60	60	180	60	60	180	60	60	180	60	60	180

Simulation Results

It can be seen from Figure 7.22 that, test case 2 and 4 appears to be the best conditions for the older person amongst the real life test cases simulated even though the recorded body core temperature at the end of the exposure (300min) was 0.8°C below the baseline of 37°C. In all the seven test cases, after the exposure to the winter conditions with the subject coming back into the room, the core temperature continued to fall in the older person. Compared to the average person in Figure 7.23, in two test case (test case 2 and 4), the core body temperature stopped falling and maintained a constant value. The continuous fall in the core body temperature of the older person can be attributed to the reduction in the muscle mass of the older person leading the a reduced ability to generate enough heat for maintaining body core temperature (Taaffe and Marcus, 2000, Knight and Nigam, 2008).

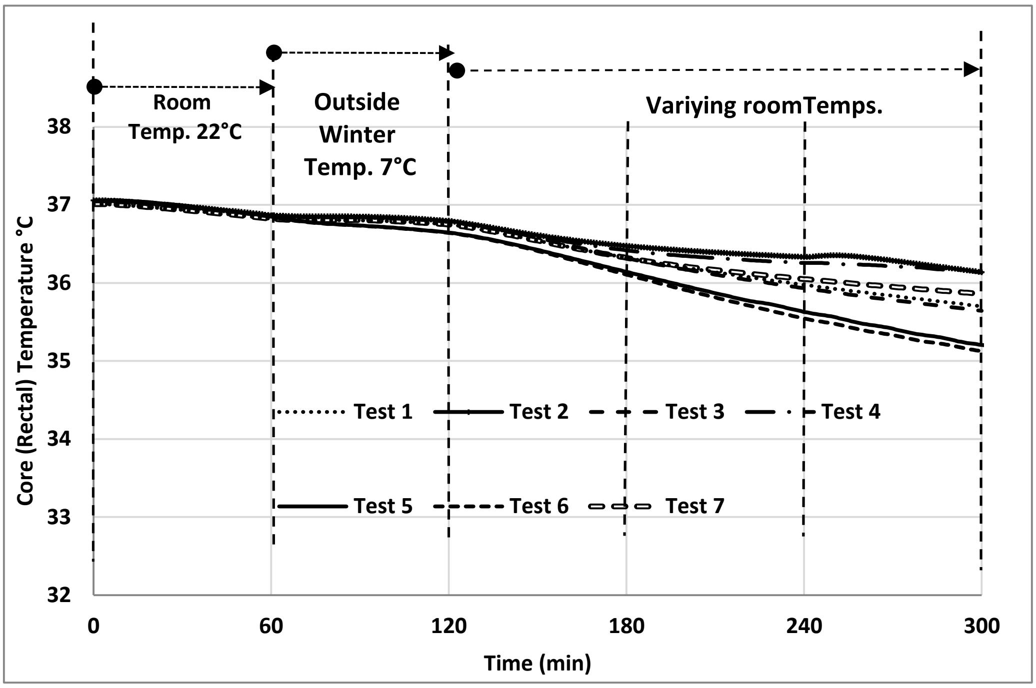

Figure 7.22 Simulation results for older persons

Test cases 5 and 6 fit into the contest of keeping the temperature low to save money on bills and it shows the rate of cooling of the body after the exposure to the cold was more severe in the older person. At the end of the scenario (300min) the fall in core temperature was 35.1°C which accounts for a 1.9°C fall drop from the baseline temperature of 37°C. This reading could as well trigger thermal accidents for example mild hypothermia and put the health and wellbeing of the older person at risk. In comparison to the average person, the fall in core body temperature from the baseline value for test 5 and 6 was less than that of the older person (1.02°C). From these results, it can reasonably be concluded that test case 5 and 6, are not suitable profiles because of the serious effects they have on the thermal balance of both the average person and the older person.

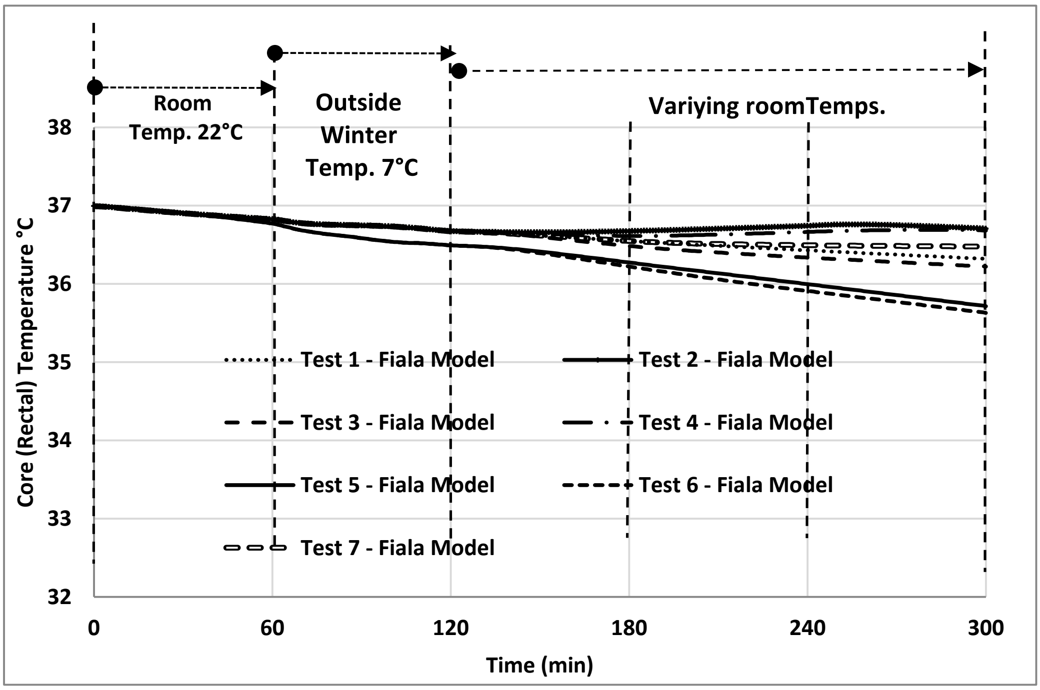

Figure 7.23 Simulation results for younger persons

From Figure 7.22, the results of test case 1 and 3 show that the fall in the core body temperature (1.2°C) was not as much as that of test case 5 and 6 in the older person and the same pattern can be seen in the average person (Figure 7.23). These results confirms what (Guerra-Santina and Itarda, 2010) said that, ‘in household where older persons are present the pattern of use of heating and ventilation system are affected’.

Test case 7 is a representation of test case 1 but with further clothing insulation after 1 hour when the subject returned from the walk. As can be seen from Figure 7.22, when the insulation was increased from 0.9clo to 1.3clo the increase in the core body temperature at the end of exposure was 0.16°C which was not enough to raise the body temperature to the baseline condition. The average person’s predictions however show a positive increase in the core temperature moving closer to the baseline temperature. Indeed these results reveal the challenges older persons face in the control and of their core body temperature.

The result agrees with a real life experience of an older person who was interviewed in the work done by Age UK (2012). According to the older person *“you put on layers and layers to keep yourself warm, but even though you dress up you are still cold”* (Age-UK, 2012). These situations may mostly be as a result of the collective effect of ageing of the body systems of the older persons including reduced cardiac output, reduced muscle mass, reduce temperature sensitivity and reduction in basal metabolic rate (Anderson et al., 1996, Brandfonbrener et al., 1955, Hyatt et al., 1990, Aniansson et al., 1986, Chumlea et al., 1999, Henry, 2000, Van Pelt et al., 2002).

7.18 Summary of interview study

The results of the interview revealed the following:

- That the model is a valuable tool to assist in further understanding the thermal behaviour of the older person.
- The flexibility of the model in carrying out several test cases to predict the body core temperature of the older person has been established.
- The results of the model could potentially be used to support awareness creation campaigns about thermal management amongst older persons.

7.19 General Summary

In this section, the validated Older Persons Model was applied to several test cases extracted from published literature. The results of the model have shown good agreement with published findings on the thermal behaviour of the older person. Results from the interview conducted revealed that the Older Persons Model could be a valuable tool for the determination of thermal response pattern of the older person in relation to varying environmental conditions. The models results from real life test cases follow the expected response patterns of the older persons based on published literature.

Chapter 8

Conclusion and future work

8.1 Introduction

This thesis aims at adapting an existing human thermoregulation model for predicting the thermal response of older people. This was based on the information that useful insights can be gained for the future design of the built environment from modelling the thermal behaviour and response patterns of older people. This is vital since many research findings have revealed that 20% of the world's population is likely to be over 60 years by 2050 (see Chapter 1 and 2). This chapter summarises the research study and discusses how its findings addressed the main aim. The contribution of this research to existing knowledge and the future work is also presented.

8.2 Summary of research study

The contribution of this thesis emerges from the systematic review of literature on the inherent effect of ageing on the physical and thermo-physiological system of the older people which in turns affects their thermal balance (see Chapter 2). Futher literiture review was carried out on existing thermoregulation models in practice and an establised model (Fiala Model) was selected for adaptation (see Chapter 3). A critical review of the selected model gave insight into the data needed for its modification in order to reflect the thermal behavior of older persons. Comprehensive literiture review was conducted to collate related and relevant experimental data sets for the modification process. In doing this, it was discovered that whiles many experimental studies on the thermal behaviour of young persons exist, that of the older person was limited.

The collected data was analysed and divided into two groups and used for modifiying the passive system (see Chapter 4) and active system (see Chapter 5). The passive system was modified by the replacement of the various body parameter values in the Fiala model with new sets of values sourced from literature related to body composition of the older person thus creating a Typical Older Person passive system (see Chapter 4). The active system was also modified based on established scientific information from literature that age related changes in thermal sensitivity, perception significantly alters structures, and functions of the nervous system (see Chapter 5). An advanced optimisation package with the capability of taking the limited data sets and using it to navigate through huge search spaces to determine the best-fit coefficients for the older person's active system (central nervous system) was used. The selected optimisation package undertakes its processes by the working principles of Genetic Algorithms (GA) which are computer based search techniques inspired by the process of evolution of biological organisms.

After several optimisation runs new set of coefficients were developed which were implemented in the model thus creating the Older Persons Model. The predictions of the Older Persons Model were evaluated against the experimental data using various statistical metrics to determine the goodness of fit (see Chapter 6). Model application was undertaken in Chapter 7.

8.3 Conclusion

In conclusion, a new modified thermoregulation model for predicting the thermal response of older persons has been developed based on experiments extracted from published literature. The verification exercise undertaken shows that the new model reasonably reproduced experimental data and validation results also reveal that the model reproduced well the independent experimental data which were not used in the model development. The main features of the new model consisted of the passive system (body structure of older persons) and the active system (control system-Central nervous system of older persons). These have been explained and justified with supporting references and evidence provided. In general, the Older Persons Model shows good predictive ability in terms of predicting for the older persons body core temperature, which is one of the most vital body parameters, used in analysing the thermal behaviour of the older person. Indeed the statistical metrics analysis of the predictions of the core temperature of Older Persons Model both in the validation and verification process points to a strong correlation with the original Fiala Model used for the predictions of young subjects.

Significant improvements in predicting the core temperature of the older person was recorded by the Older Persons Model with coefficient of determination (0.90) for the core body temperature and (0.87) for the mean skin temperature predictions. In contrast, the Fiala Model with older person's body had a coefficient determination value of 0.33 for the core body temperature and 0.89 for the mean skin temperature predictions. Whilst the Fiala Model used for older person has had a coefficient determination value of 0.63 for the core body temperature and 0.86 for the mean skin temperature predictions. In a comparative analysis in the context of their respective fields of application, i.e. Fiala Model used in predictions for the young the coefficient of determination in respect of core temperature for the Older Persons Model was 0.90 whiles Fiala model used for young person's predictions was 0.87. In the case of mean skin temperature, Older Persons Model had 0.87 for coefficient of determination and Fiala Model had 0.87.

This range of values underlines the strong correlation between the predictive capabilities of these models in their respective fields of application. This therefore confirms that, the Older Persons Model for the range of experiments used in this study predicts well for the older person, as does the original Fiala Model capability to predict for the young person although there exist limitations.

A study carried out on the application of the model using test case scenarios extracted from published literature showed general good agreement of the model with the perceived thermal response of the older people. Practitioners particularly building services specialists and mechanical engineers, found the Older Persons Model very useful in assisting to further understand the thermal response of the older people based on semi-structured interviews conducted on a limited number of interviewees. Furthermore, it was found that the models results could be used to assist in campaign activities aimed at creating awareness on how to effectively manage the thermal environment for the older persons to preserve life and wellbeing.

In all, the current model has **four** main applications:

- **One:** For predicting older person’s temperature distribution in different environmental conditions during design stage of a built environment where older persons may be in the majority.
- **Two:** It can be used as a test tool for quick evaluation of the thermal states in existing occupancies to inform decision on interventions to be included in order to improve comfort.
- **Three:** The proposed methodology could potentially help to easily understand the ageing effect on the parameters of the body and the control systems that govern thermoregulation within the body and also identify high-risk scenarios for prioritizing housing improvements designed to provide affordable warmth for the older population.
- **Four:** If the current model is further refined and validated, it could provide baseline information for health impact assessment of older people.

8.4 Contribution to knowledge

The primary contribution to knowledge from this study is the development and validation of a human thermoregulation model for the older persons. This fills the gap in the literature on existing research on human thermoregulation modelling which has yet to address the effect of the ageing phenomenon on the body in detail. The model is of value in that it enables detailed simulation of the thermal behaviour and response patterns of the older person to be evaluated in varying environmental exposures. In addition, using the model to explore various real life patterns of thermal management profiles and their influence on the older person’s body has resulted in a number of insights into its significance.

Furthermore, in order to evaluate its predictive capability, the original Fiala Model was applied to the experimental test cases of older subjects and its results compared with that of the Older Persons Model. The results from this study adds to the debate that having a detailed human thermoregulations model for the older population is a necessity especially in the current era of ageing of populations around the world and the erratic climatic variability.

The thesis has also provided original contribution in terms of methodology (a novel approach for modelling the active system-central nervous system) by the use of an optimisation approach based on the principles of Genetic Algorithms.

8.5 Authors reflections on the Model

Review of literature revealed the shortcomings of the current average models of thermoregulation and illuminates the need for a more representative model for the older population. Whiles this need was clear, availability of sufficient experimental data of older people was limited (Chapter 5). However, diligent effort was made to search several databases in order to collate relevant and related published experimental data sets for the model development.

Furthermore, a review of literature in other fields of study revealed that, the problem of inadequate experimental data of the older people was not peculiar to the field of human thermoregulation modelling. Indeed Watts (2012) in his work titled "*why the exclusion of older people from clinical research must stop*" points out that while clinical trials of other cohorts of the population was well documented and discussed. The same cannot be said of the older people arguing that older people are proportionally under represented or even absent from most drug trials (Watts, 2012). McMurdo et al. (2011) adds that exclusion of older people from clinical research and under-recruitment to clinical trials was widespread. Fawcett (2012) in agreeing with Watts (2012) concedes that in spite of the number of physiological and pathological changes that may be occurring in the elderly, *"it was essential that this group of the population is offered opportunities to be part of experimental trails to enable them also benefit from medical advances".*

Kunkler (2012) agrees with Watts (2012) saying barriers to recruitment of older patients in randomized trials needed to be addressed. Marion McMurdo, a Professor of Aging and Health at University of Dundee, affirms that a multi-facetted approach is required to end the systematic exclusion of older people from clinical research (McMurdo, 2012). McMurdo (2012) points out that

> *"A zero tolerance policy from both funders and ethics committees for arbitrary upper age cut-offs could be one measure which could have a major impact on the situation".*

According to McMurdo et al. (2005), the use of upper age limits was surprisingly common with 33% of papers published in four leading medical journals using explicit exclusions on the basis of age. McMurdo (2012) notes that "*in many instances; researchers simply opt for an upper age limit on a purely arbitrary basis, without offering a scientific justification for why"*. NCCEH (2010) in its work looking at *"the possibilities and limitation of acclimatization for protections against extreme heat"* points out that whiles there exist some information on acclimatization of older people to heat in order to build up their physiological defences, what was unclear was the degree to which they should. Indeed after a thorough search of literature NCCEH (2010) concluded that whiles there exists extensive experimental studies of young fit men exposed to various environmental conditions, they were unable to find experimental studies of acclimation using subjects older than 60 years. Out of all literature they reviewed on the subject matter (acclimatization), only two related studies based on older men were found and these dates back to 1965 and 1970 (Robinson et al., 1965, Lind et al., 1970).

With reference to the work of Lind et al (1970), while the average age of the younger group was 27 years (23 to 31 years) that of the older group was 47 years (39 to 53 years). However Robinson et al. (1965) used a mean age of 52 years for the older people. These ages clearly fall short of the cohorts considered the older people who are mostly regarded as people above 60 years of age. Whiles issues can be raised about the age range of the older people as to whether their body compositions can effectively represent that of the older person, the time of the experiment (1965 and 1970) is also an issue to be considered and the amount of related experimental studies undertaken since then.

These findings thus underpin the need for the research community to take more interest in experimental studies involving the older people especially in the field of human thermoregulation. This will go a long way to generate more information on the thermo-physiological behaviours of the older people which will help in the design of more robust and effective models which can be used to assist in the design of better and well-suited environments for the older people. As good as this may sound, there are hurdles which need to be crossed in terms of ethics, demands of funding bodies and physiological and pathological changes in the older people. As pointed out by McMurdo (2012),

"only a zero tolerance policy from both funders and ethics committees for arbitrary upper age cut-offs to be looked at could well be one measure which could have a major impact on the situation".

8.6 Future Work

This section introduces some of the important features, which will be added to the current Older Persons Model to make it more robust in the future.

- The current Older Person's Model uses only 15 test cases from various experiments for the calibration and validation processes. These data sets limit the models capabilities as compared to the Fiala model, which had much larger data sets. Further development needs will be the addition of many more experiments of older persons.

- The experiments used for the development of the older persons model were not designed for modelling purposes as such many did not report on some of the parameters which are vital to the modelling process. Further development needs will be the design of experimental trails aimed specifically at collating relevant data for modelling older persons thermal system. More experiments are needed for the sweating potential of older persons, the total average shivering potential, and skin sensitivity values. To ensure uniformity, similar or same formulae for mean skin temperature measurement should be used.

- The current model profiles fat distribution within the body based on the profile set in the Fiala Model but research has revealed that there is an increased deposition of fat around the waist area as the body ages. Further development needs will be the varying of the of the percentage fat distribution over the body surface since it will be more representative of the body structure of the older person. As to whether the fat accumulation around the waist has effect on the thermoregulation and thermal response of the older person could be further investigated.

- The current model focused on the typical older person but research also reveal that in the cohort of the older persons, they can be further divided into various groups depending on their body composition and physiological behaviours. Some studies proposed groupings of the elderly as
    - Young old (65-75)
    - Middle Old (75-85) and
    - Oldest old 85+ years.

  The current methodology can be adopted for use in the further design of models for the three major cohorts of the older population when more data becomes available.

- The validation test cases used in this thesis were performed in climatic test chambers, it is envisaged that future validation test cases based on responses of building occupants and measurements of their body parameters will further improve the model.

- The thermal comfort model in the original Fiala Model was not modified due to lack of sufficient data. Further development needs will be the collation of more data involving thermal comfort results of older persons exposed to varying thermal conditions.

Even though the Older Persons Model, presented in this thesis, has some limitations and the proposed future work will definitely lead to substantial improvements in its capabilities, the findings in this research show that it predicts the thermal behaviour of the older person with a good degree of certainty.

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List of Authors Publications

1. **Novieto DT** and Zhang Y, Towards thermal comfort prediction for the older population: a review of aging effect on the human body, IESD PhD Conference, **Leicester UK**, 1, pp 35-48, (2010), 978 185 721 4079,
2. **Novieto DT** and Zhang Y, Aging and thermal comfort modelling, Junior Scientist Conf 2010, 07-09 April, **Vienna Austria**, pp 331-332, (2010), ISBN 978-3-200-01797,
3. **Novieto DT** and Zhang Y, Thermal comfort implications of the aging effect on metabolism, cardiac output and body weight, NCEUB Windsor Conf 2010, 09-11 April, **Windsor UK**, pp 1-11, (2010),
4. Zhang Y, **Novieto DT** and Ji Y, Human environmental heat transfer simulation with CFD – the advances and challenges, IBPSA BS2009, 27–30 July, **Glasgow Scotland**, pp 2162-2168, (2009)

Appendix A

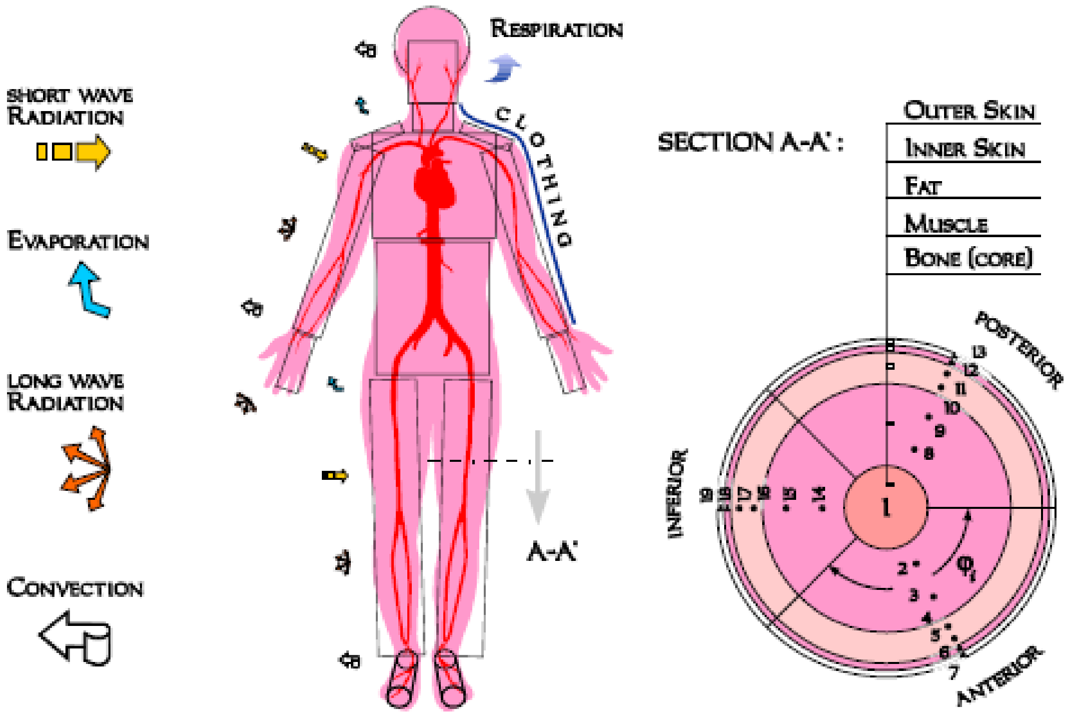
Values of various activity levels

Activity	W/m^2	Met
Reclining	**46**	**0.8**
Seated relaxed	**58**	**1**
Standing relaxed	**70**	**1.2**
Sedentary activity(office, dwelling, school, laboratory)	**70**	**70**
Car driving	**80**	**1.4**
Graphic profession – Book Binder	**85**	**85**
Standing, light activity (shopping, laboratory, light industry)	**93**	**1.6**
Teacher	**95**	**95**
Domestic work – shaving, washing and dressing	**100**	**1.7**
Walking on the level, 2 km/h	**110**	**1.9**
Standing, medium activity (shop assistant, domestic work)	**116**	**2**
Building industry – Brick laying (Block of 15.3 kg)	**125**	**2.2**
Washing dishes standing	**145**	**2.5**
Domestic work – raking leaves on the lawn	**170**	**2.9**
Domestic work- washing by hand and ironing (120-220 W)	**170**	**2.9**
Iron and steel – ramming the mould with a pneumatic hammer	**175**	**3**
Building industry – forming the mould	**180**	**3.1**
Walking on the level, 5 km/h	**200**	**3.4**
Forestry – cutting across the grain with a one-man power saw	**205**	**3.5**
Volleyball	**232**	**4**
Calisthenics	**261**	**4.5**
Building industry-loading a wheelbarrow with stones and mortar	**275**	**4.7**
Bicycling, Golf, Softball	**290**	**5**
Gymnastics	**319**	**5.5**
Aerobic Dancing, Basketball, Swimming	**348**	**6**
Sports – Ice skating, 18 km/h 360 6.2	**360**	**6.2**
Agriculture – digging with a spade (24 lifts/min.)	**380**	**6.5**
Skiing on level, good snow (9 km/h), Skating ice, Tennis	**405**	**7**
Forestry – working with an axe (weight 2 kg. 33 blows/min.)	**500**	**8.5**
Sports – Running in 15 km/h	**550**	**9.5**

Table 1.3 metabolic Rates (Grimpampi, 2009)

Appendix B

The passive system of the Fiala model



Source (Fiala, 1998)

Appendix C

Individual tympanic temperature (Tty) thresholds for cessation of sweating and onset of shivering and the magnitudes of the null-zone.

	Gender	Tty(rest)	Tsw	Tsh	NullZone
Young					
1	M	37.3	0.3	-0.3	0.6
2	M	37.5	0.2	-0.4	0.6
3	M	36.9	0.3	-0.1	0.4
4	M	37.3	0.2	-0.2	0.4
5	M	37	0.2	-0.1	0.3
6	M	37	0.1	-0.2	0.3
7	M	36.7	0.3	-0.2	0.5
8	M	36.7	0.1	-0.2	0.3
9	M	37	0.2	-0.3	0.5
Mean		37.1	0.2	-0.2	0.4
SD		0.3	0.1	0.1	0.1
Elderly					
1	M	36.9	0.2	-0.4	0.6
2	M	36.6	0.4	-0.9	1.3
3	F	37.1	0.5	-0.3	0.7
4	M	36.7	0.5	-1.3	1.8
5	M	37.2	0.6	-0.4	1
6	M	36.4	0.6	-0.6	1.2
7	F	36.8	0.7	-0.9	1.6
8	M	36.9	0.2	-0.7	0.9
9	M	36.1	0.6	-0.3	1
Mean		36.7	0.5	-0.6	1.1
SD		0.3	0.2	0.3	0.4

Source (Anderson et al., 1996)

Appendix D

Model Results step 1

Core temperature

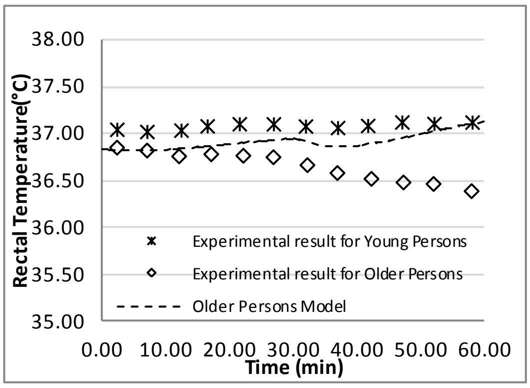


Figure E.1 Experimental exposure of 5°C

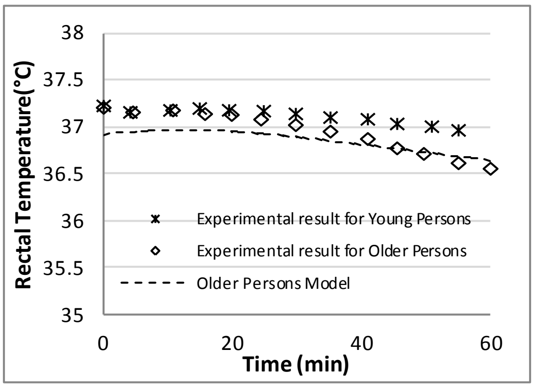


Figure E.2 Experimental exposure of 12°C

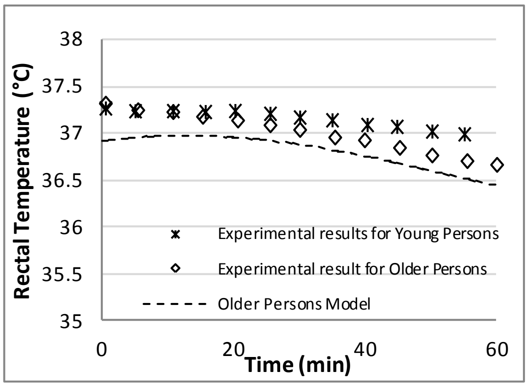


Figure E.3 Experimental exposure of 17°C

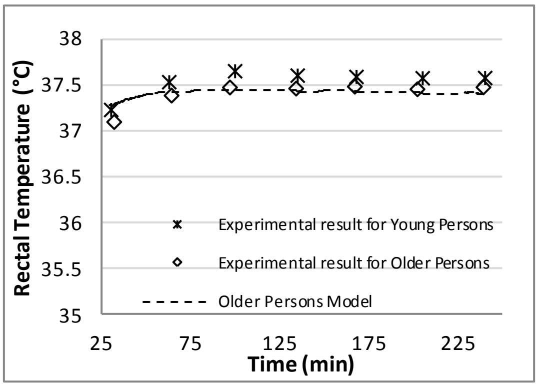


Figure E.4 Experimental exposure of 21°C

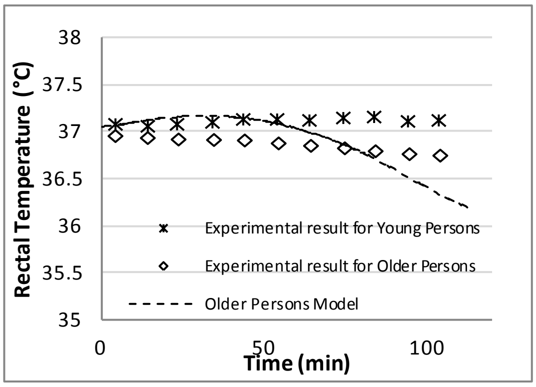


Figure E.5 Experimental exposure of 26°C

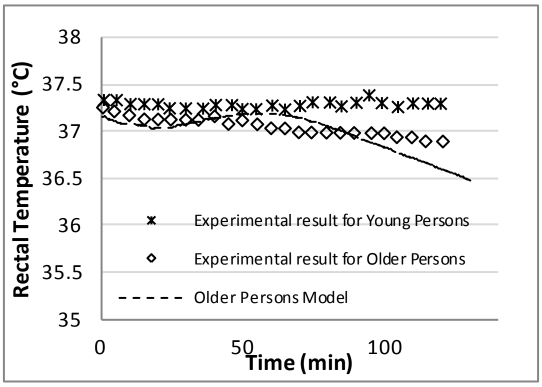


Figure E.6 Experimental exposure of 28°C

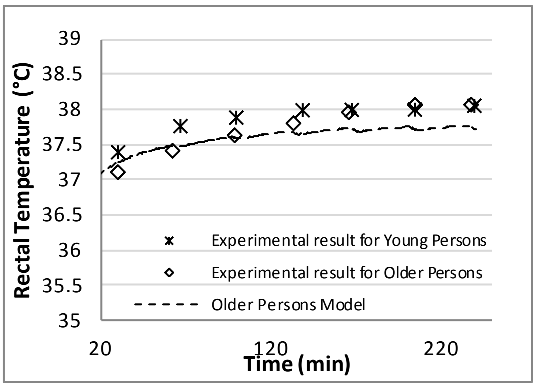


Figure E.7 Experimental exposure of 30°C

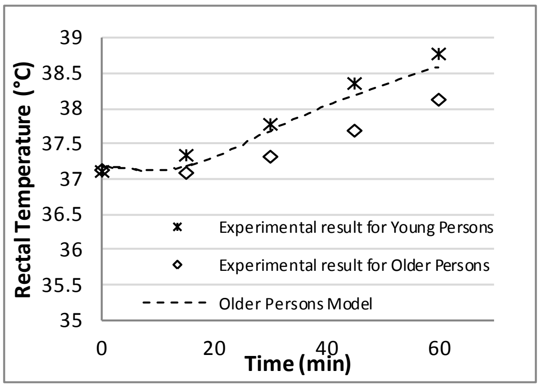


Figure E.8 Experimental exposure of 42°C

Mean Skin temperature

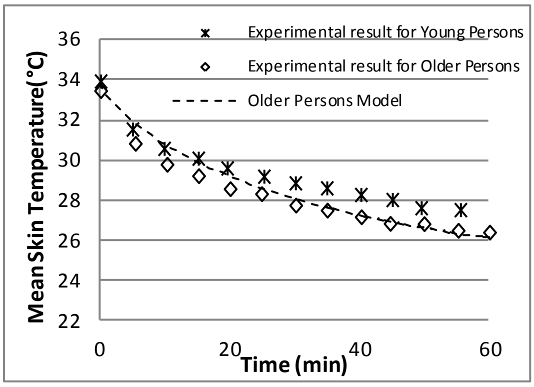


Figure E.9 Experimental exposure of 12°C

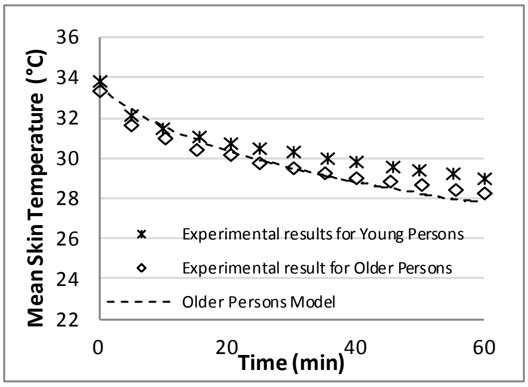


Figure E.10 Experimental exposure of 17°C

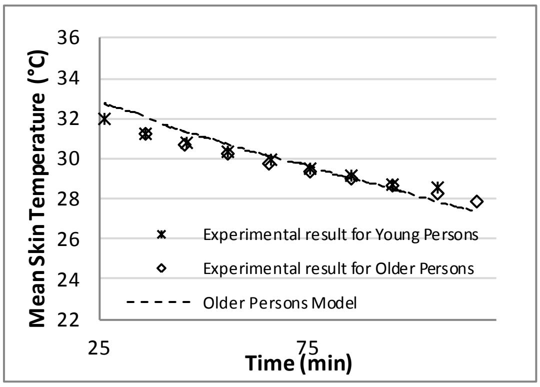


Figure E.11 Experimental exposure of 26°C

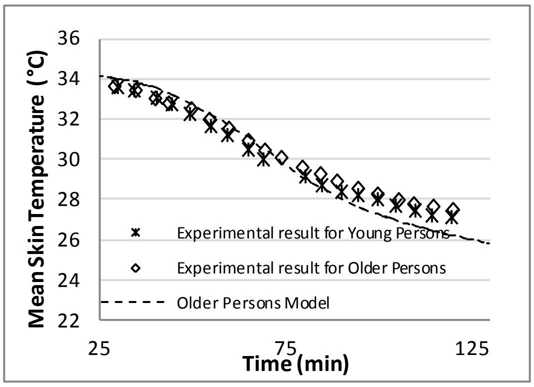


Figure E.12 Experimental exposure of 28°C

Appendix E

Fiala Model results in comparison with younger subjects experimental results

Core Body Temperature - Verification

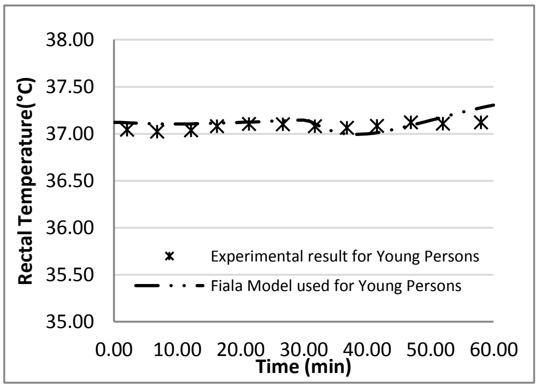


Figure D.1 Experimental exposure of 5°C

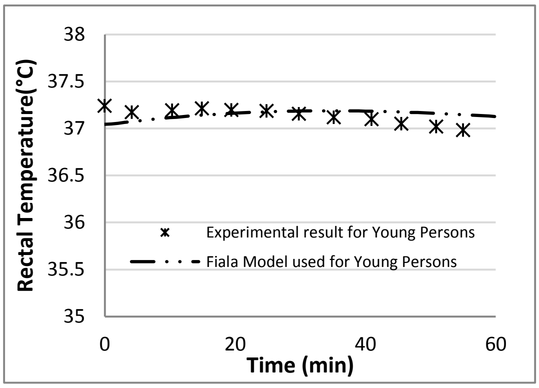


Figure D.2 Experimental exposure of 12°C

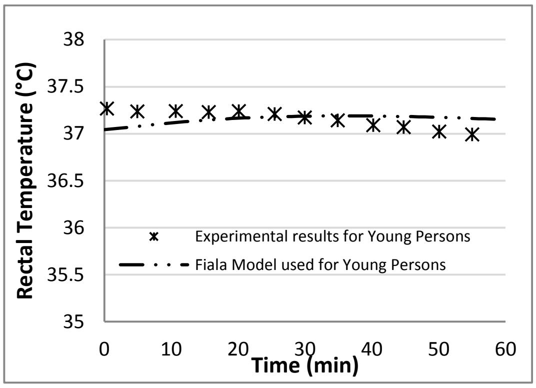


Figure D.3 Experimental exposure of 17°C

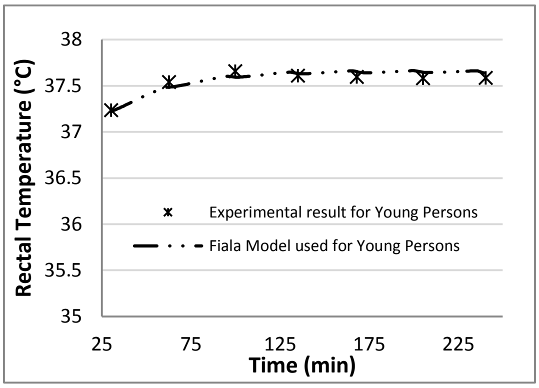


Figure D.4 Experimental exposure of 21°C

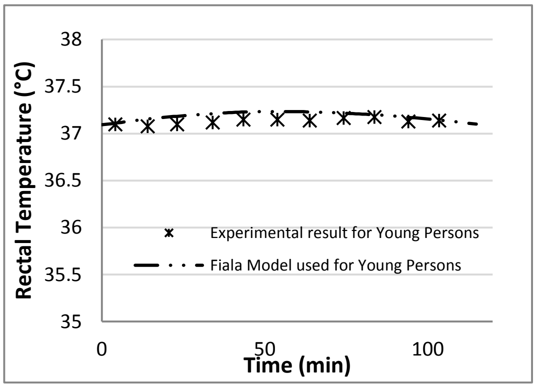


Figure D.5 Experimental exposure of 26°C

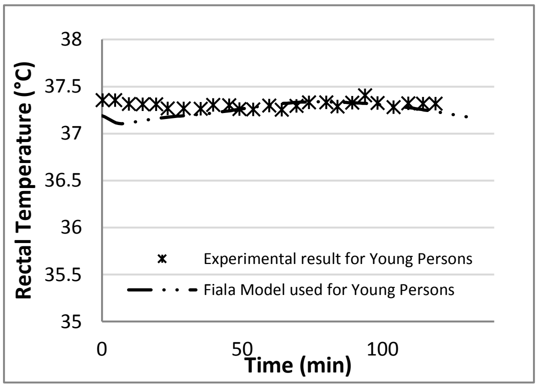


Figure D.6 Experimental exposure of 28°C

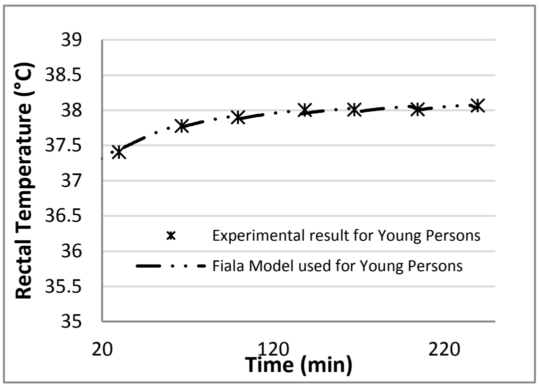


Figure D.7 Experimental exposure of 30°C

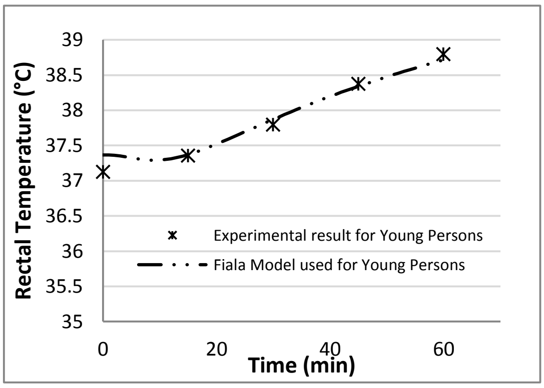


Figure D.8 Experimental exposure of 42°C

Validation

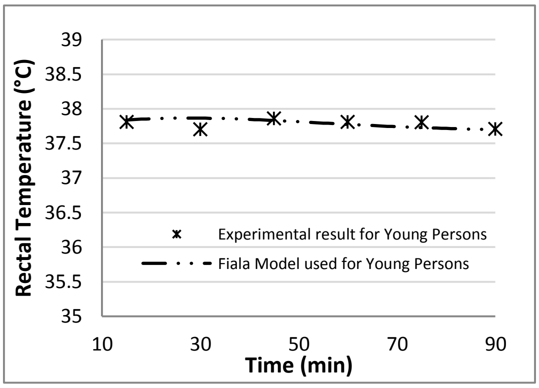


Figure D.9 Experimental exposure of 8°C

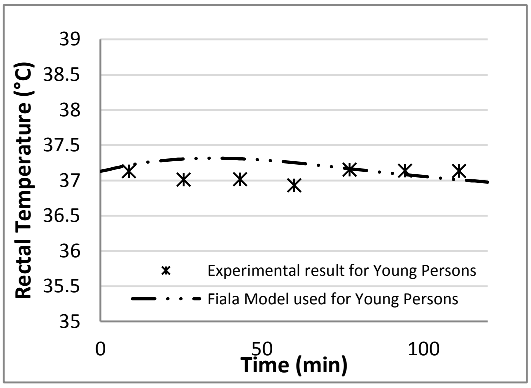


Figure D.10 Experimental exposure of 12°C

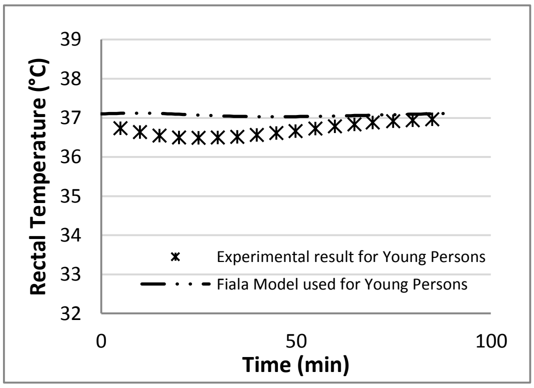


Figure D.11 Experimental exposure of 40°C

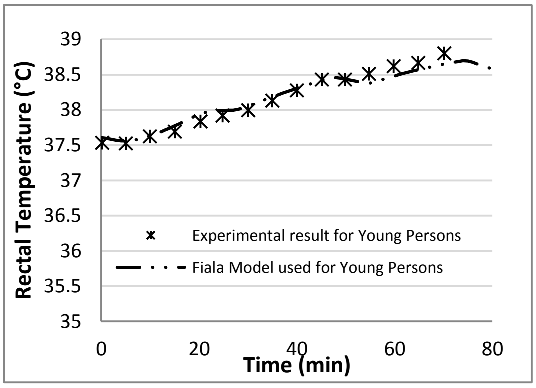


Figure D.12 Experimental exposure of 41°C

Mean Skin Temperature Verification

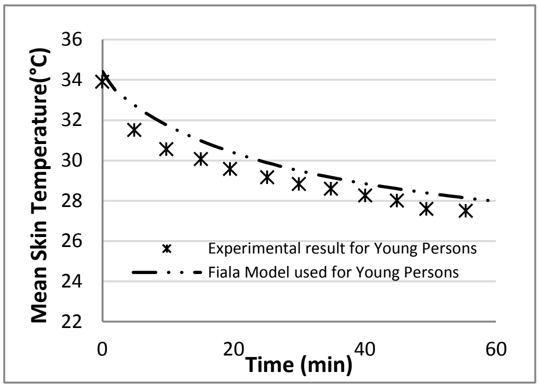


Figure D.13 Experimental exposure of 12°C

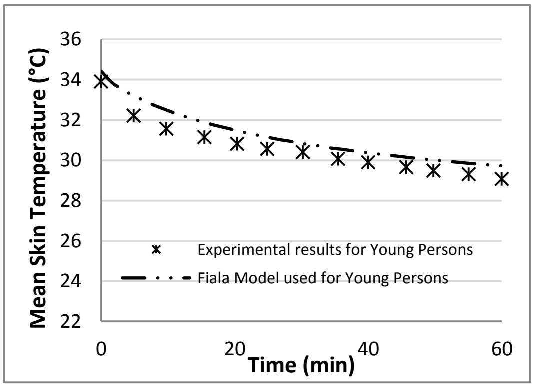


Figure D.14 Experimental exposure of 17°C

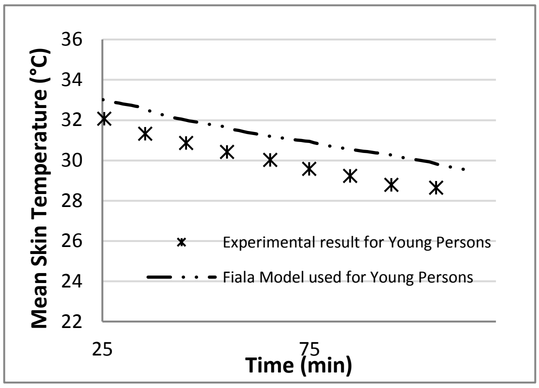


Figure D.15 Experimental exposure of 26°C

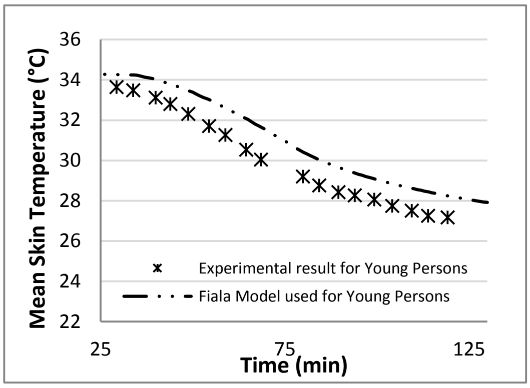


Figure D.16 Experimental exposure of 28°C

Validation

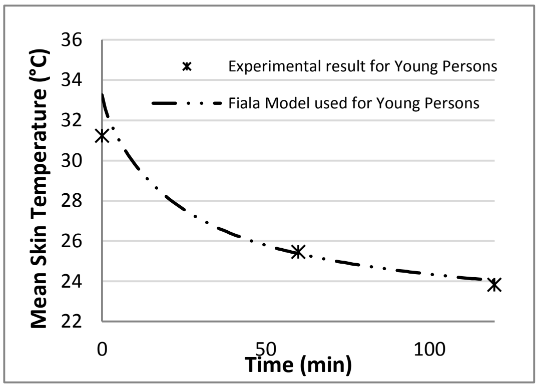


Figure D.17 Experimental exposure of 10°C

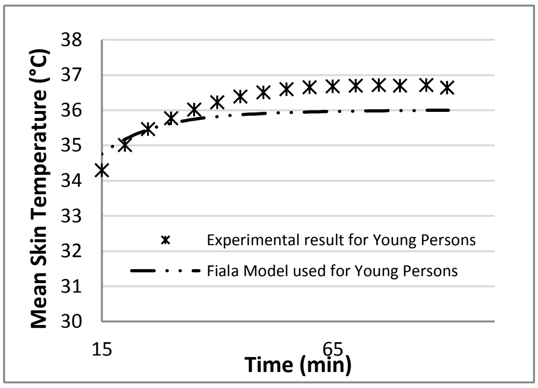


Figure D.18 Experimental exposure of 40°C

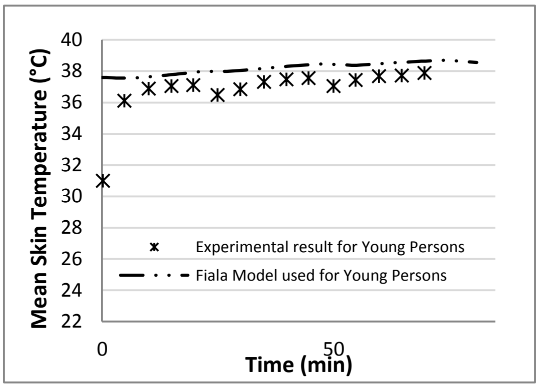


Figure D.19 Experimental exposure of 41°

Appendix F

Sample Interview questions

1. The world is ageing rapidly with increased number of older person, tell me about the impact these challenge have on your world of work.
2. Can you briefly tell me about the current and future dimensions of thermal comfort and modelling of thermal comfort?
3. Human thermoregulations models have been in existence for over four decades now how relevant are they to your field of work.
4. Most of these models have been designed to predict for the average persons, what is your view about these models being used for older person’s predictions.
5. What is your view about a customized model for the older person?
6. What are some of the characteristic you would like to see in the older person’s model
7. What are some of the areas you think the model could assist you?
8. What comments do you have about the outputs of the model?
9. What other suggestions do you have to give in line with the current project?